Getting SSL to Market

Solid-State Lighting Workshop

U.S. Department of Energy
January 31 - February 2, 2007
Phoenix, Arizona

Lighting Research and Development
Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

March 2007

2007 DOE Solid-State Lighting Workshop Report

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Prepared for:
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ACKNOWLEDGEMENTS

The Department of Energy would like to acknowledge and thank all the participants for their valuable input and guidance provided during the 2007 DOE SSL Workshop. The Department would also like to thank all the direct contributors and especially the following individuals:

Srinath Aanegola, GELcore
Gregg Ander, Southern California Edison
Rolf Bergman, CIE/USA
James Brodrick, U.S. Department of Energy
Paul Burrows, Pacific Northwest National Laboratory
C. Edward Christy, National Energy Technology Laboratory
Kevin Dowling, Next Generation Lighting Industry Alliance
Anil Duggal, GE Global Research
David Elien, GELcore
Tim Fitzsimmons, U.S. Department of Energy
Kelly Gordon, Pacific Northwest National Laboratory
Dawn Hollingsworth, Visual Terrain
Marc Ledbetter, Pacific Northwest National Laboratory
Cynthia Merrell, LED Lighting Fixtures
Ann Norris, Dow Corning
Jeff Quinlan, Acuity Brands Lighting
Paul Thurk, ARCH Venture Partners
Fred Welsh, Radcliffe Advisors

This report was prepared for the U.S. Department of Energy and the National Energy Technology Laboratory by Akoya under NETL Order Number: DE-AD26-03NT30656.

COMMENTS

The Department of Energy is interested in feedback or comments on the materials presented in this Workshop Report. Please write directly to James Brodrick, Lighting R&D Manager:

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1. Introduction

More than 250 attendees gathered in Phoenix, Arizona, to participate in the 2007 Solid-State Lighting (SSL) Program Planning Workshop, hosted by the U.S. Department of Energy (DOE). Lighting industry leaders, fixture manufacturers, researchers, academia, trade associations, energy efficiency organizations, and utilities joined DOE to share perspectives on the rapidly evolving SSL market. The workshop provided a forum for building partnerships and strategies to accelerate technology advances and guide market introduction of high efficiency, high-performance SSL products.

The fourth annual DOE SSL workshop focused on "Getting SSL to Market." The Department has developed a comprehensive national strategy for guiding SSL technology from laboratory to marketplace. This strategy draws on key partnerships with the SSL industry, research community, standards setting organizations, energy efficiency groups, utilities, and others, and includes Basic Energy Science, Core Technology Research, Product Development, Commercialization Support, Standards Development, and an SSL Partnership.

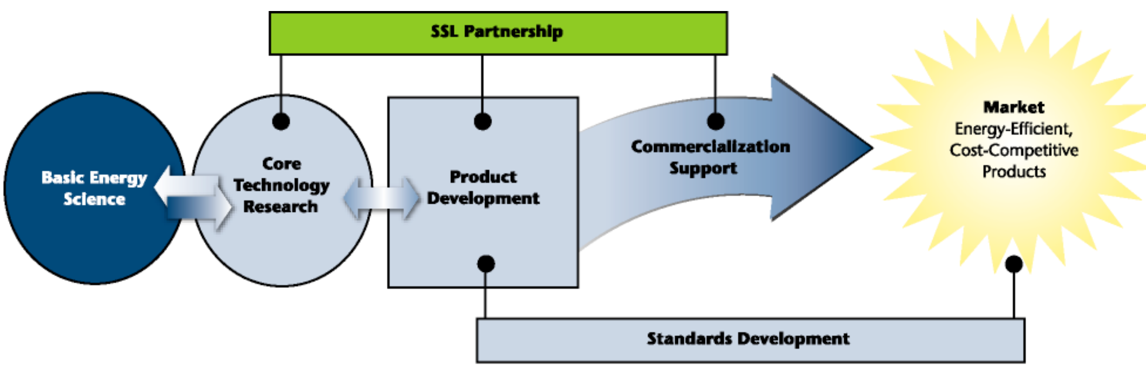


Figure 1-1: DOE Solid-State Lighting Portfolio

In recent decades, U.S. researchers have made substantial progress in improving the performance and lowering the cost of light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs). The pace of technological progress in SSL is accelerating rapidly, and SSL technology is poised to take a major role in the general illumination market. DOE's leadership and support acts a catalyst to guide SSL technology and the market to the highest level of efficiency and performance possible.

Chapter 2 of this report details perspectives and strategies from industry leaders working to "get SSL to market." In Chapter 3, DOE provides an overview of the SSL research and development (R&D) portfolio, an update from the Basic Energy Sciences (BES) program about BES research related to SSL, and guidance on preparing a comprehensive application for DOE R&D funding.

Chapter 4 focuses on lighting design, including the Lighting for Tomorrow Design Competition as well as insight about what architects and designers want from SSL. Chapter 5 focuses on ways that government and private-sector organizations are guiding market introduction of SSL products. Chapter 6 describes the discussions and conclusions from the R&D Priorities breakout sessions, where workshop participants reviewed and commented on proposed updates to the DOE SSL R&D roadmap. In Chapter 7, DOE details upcoming program activities and events.

Workshop presentations and materials referenced in this report can be found on the SSL website at http://www.netl.doe.gov/ssl/materials_2007.html.

2. Strategies for "Getting SSL to Market"

The 2007 DOE SSL Workshop began on January 31, 2007, with an introduction by James Brodrick, DOE SSL Portfolio Manager. Brodrick outlined DOE's national strategy for "getting SSL to market," and invited participants to listen to the varied perspectives offered by David Elien, CEO of GELcore; Paul Thurk, Principal at ARCH Venture Partners; Jeff Quinlan, Director of Engineering for Acuity Brands Lighting; and Cynthia Merrell, CFO of LED Lighting Fixtures. Kevin Dowling, Chair of the Next Generation Lighting Industry Alliance, described how the Alliance contributes to "getting SSL to market," and invited participants to join.

2.1 Welcome and Overview

James Brodrick, U.S. Department of Energy

James Brodrick welcomed over 250 participants to the Fourth Annual DOE SSL Workshop by highlighting several recent industry announcements that underscore the rapid pace of SSL technical advances. "The next few years represent a window of opportunity as efficacy improvements ramp up and costs ramp down," Brodrick said. "But R&D alone is not enough. Efficacy improvements, alone, are not enough. To actually save energy, we have to get SSL to market."

Brodrick noted that early adopters like Wal-Mart and California Home Builders are encouraging widespread use of new SSL technologies. Wal-Mart has made a corporate commitment to install LED-based lighting in refrigerator display units in stores across the country. The California Home Builders will participate in SSL demonstrations this summer. Federal agencies such as the DOE Federal Energy Management Program and the departments of Defense, Commerce, and Agriculture are also stepping up to identify opportunities for volume purchases and host buildings for SSL demonstrations.

Brodrick emphasized the challenges and opportunities facing the U.S. lighting industry. The unique attributes of SSL will lead to new forms and functions for lighting, and trigger fundamental changes in the lighting industry value chain and how lighting is delivered to market. The transition to SSL will require coordinated industry-wide solutions and national leadership.

DOE has developed a comprehensive national strategy to guide SSL technology from lab to market. The Department's support acts as a catalyst from end to end, and key partnerships with the SSL industry, research community, standards setting organizations, energy efficiency groups, utilities, and others guide DOE planning every step of the way.

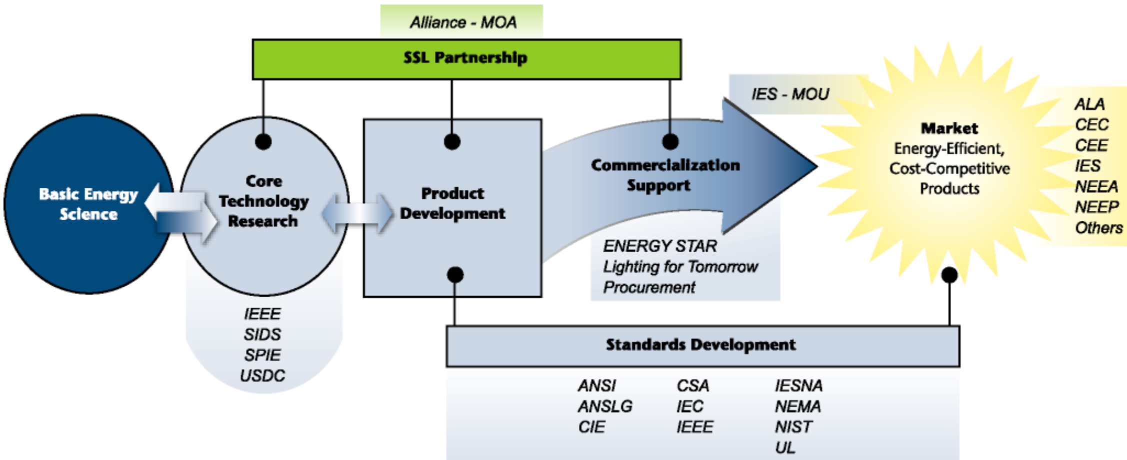


Figure 2-1: DOE Lab to Market Strategy and Partners

"The market challenges we face are complex, and DOE is stepping up to the challenge – focusing its resources in strategic areas that foster the growing market for high performance, high efficiency SSL products," Brodrick concluded. "You have an opportunity to partner with DOE and others, and join in the evolution of the U.S. lighting industry."

2.2 Meeting the LED Lighting Challenge

David Elien, GELcore

David Elien, CEO of GELcore, was only partially joking when he said, "I'm not a light bulb guy, I'm an LED guy. When I get up in the morning I'm looking to kill a light bulb."

Elien shared insights on GELcore's customer focus, highlighting GELcore's partnership with Wal-Mart as an example of "using technology to create value—the Wal-Mart win," he said. The two companies have a longstanding relationship: several years ago, GELcore worked with Wal-Mart to replace the neon lights with LED in the red star signage on the outside of every store. More recently, GELcore worked with Wal-Mart to switch the lighting in commercial refrigeration cases from fluorescent bulbs to LEDs. To accomplish this, they obtained unprecedented access to Wal-Mart's operation, including the ability to collect data on lighting practices and talk to key decision makers. This process gave GELcore a "true understanding of the real cost of lighting, not just the price," Elien said.

Over the life of this 2.5 year project, GELcore succeeded in demonstrating improved product visibility in refrigerated units through better lighting, while reducing energy costs up to 78%. A major "win" was reducing maintenance by providing lighting solutions with a projected lifetime of 32,000 hours, the same as the lifetime of the refrigerated cases. So no LEDs will ever need to be changed—they will just be discarded with the refrigerated case when it wears out. All of this was accomplished while also protecting the environment by eliminating the mercury used in fluorescent lamps.

Elien believes that if the SSL industry wants to succeed it has to come up with a value story that blows people away, and the Wal-Mart story is one such "big win." Wal-Mart wants to be an early adopter to drive industry and suppliers in the direction of energy savings though SSL. The company is committed to spending a minimum of $13 million to implement this refrigerated case LED solution in 500 stores, resulting in a projected $2.6 million energy cost savings that will reduce CO_2 emissions by 35 million pounds annually, according to Elien.

Elien concluded by emphasizing that “SSL acceptance is in our hands,” and he outlined four key drivers:

- **Performance:** Improve performance in terms of efficiency, light quality, consistency, and color. Meet/manage customer expectations and your stated claims.
- **Education:** Educate customers who don’t care about lumens, but want to know how SSL is going to save them money. Success in education turns your customers into advocates of the new technology.
- **Standards:** Define standards early to raise the bar on quality while being sensitive to industry capabilities.
- **Incentives:** Offer incentives such as rebates and consider regulatory levers (e.g., California).

2.3 Funding SSL Start-ups

Paul Thurk, ARCH Venture Partners

Paul Thurk of ARCH Venture Partners, a 20-year-old venture capital (VC) firm, spoke on the topic of “Raising Money for Solid-State Lighting.” He began with an overview of typical fundraising scenarios, which included options ranging from self-funding and government grants to the ultimate goal of an initial public offering (IPO). VC firms make money when a company is bought out or goes public, Thurk said, so they are interested in investing in high growth companies that can exit (be acquired or go public) in 5 to 7 years, with a good return on investment.

Thurk provided an analysis of recent VC investments, noting that VCs have been investing $20-25 billion/year in semiconductors, energy, environmental solutions, and new materials, so SSL companies can offer good investment opportunities. However, photovoltaic solar energy technologies are attracting ten times the venture capital of SSL. To get more of this capital, Thurk said SSL companies must show that they have (1) a great team; (2) a well-differentiated product; (3) a large potential market to ensure long term growth; and (4) a clear plan that is both capital-efficient and honest.

According to Thurk, opportunities exist across the entire value chain. He offered examples of technology advances that might interest a VC, ranging from wafer and chip improvements to packaged die. Patents mean a lot to VC firms, and there are a lot of patents already out there on SSL technologies, so Thurk urged companies interested in VC funds to find some “white space”—a hole in the patent space—to establish their territory.

On the back end of the value chain, Thurk said that VCs might be interested in investing in companies with novel solutions for thermal management, complete luminaire systems, or Edison adaptors. In the end, SSL must become easy to buy and easy to use before the market will adopt them. “Easy to buy” often equates with having a well-recognized brand name, but he believes that the ENERGY STAR stamp of approval may help small companies to overcome this traditional bias.

Thurk offered one last piece of advice for SSL companies seeking venture capital: be sure to include a discussion indicating the size of the opportunities in your market plan. This is one subject that VC firms want to see in the proposal, but it is usually missing. Specifically, how big is the market for your product, and who tops the list for your first five sales calls?

2.4 What the Lighting Industry Requires from SSL

Jeff Quinlan, Acuity Brands Lighting

Jeff Quinlan, Director of Engineering for Acuity Brands Lighting, discussed "What the Lighting Industry Requires from SSL." Quinlan presented an overview of critical design considerations involved in introducing a new technology, specifying cost as the single most important factor. By this he meant total cost of ownership, from initial product cost to installation, operation, and maintenance costs. A complete, self-contained fixture must be easy to install and compatible with standard controls. "You want to make the complete fixture as 'plug-and-play' as humanly possible," Quinlan said.

Another important design consideration is light loss factor, which can result from lamp lumen depreciation, dirt build-up on the luminaire, temperature increases, equipment operation factors, and lamp burnout. Quinlan then discussed design considerations specific to SSL, including color, form factors, binning, lifetime, and lumen depreciation.

To ensure the success of SSL products in the market, Quinlan said, "Our ability to work collectively and collaboratively is most important." He cited five major needs on the road to success:

- **Standardization:** Customers need to know what to expect and how to use and maintain their SSL devices.
- **Modularity:** If 10 out of 100 LEDs burn out, where do customers go to replace them? Do they need to replace them?
- **Understanding the customer:** Some customers, like Wal-Mart, work in the building that they build and care about operating costs. Most builders just build and walk away.
- **Collaborative development:** "We want to work with you to serve customers' needs."
- **Historical conversion:** Retailers are still selling more T12s than T8 fluorescent bulbs, even though T8 is far better.

2.5 A "Real" LED Light for General Illumination

Cynthia Merrell, LED Lighting Fixtures

Cynthia Merrell, CFO of LED Lighting Fixtures (LLF), a small start-up company in Morrisville, North Carolina, demonstrated and talked about "A 'Real' LED light for General Illumination." She began by outlining the benefits of LEDs for lighting: they are energy efficient (yielding lower energy costs), long lived (yielding lower maintenance costs), environmentally safe, virtually unbreakable, and lightweight. Merrell then discussed reasons why LED lighting has not been adopted yet: not enough light output from the fixtures, too-high costs, inconsistent color quality. Merrell believes these disadvantages are the result of a "top down" approach to designing a LED light; many companies simply place existing packaged LEDs into a fixture.

Merrell then unveiled LLF's new 6" LED downlight, designed for the residential lighting market. LLF used a "bottom up" approach to develop unique solutions to address the thermal, binning, and system integration issues usually found in LED sources. For customer acceptance, Merrell says, the light must look like a real light, with a cost in the ballpark of existing lighting fixtures. LLF's five year residential payback analysis shows the cost of ownership of incandescent bulbs, fluorescent bulbs, and this 6" downlight to be $135, $72, and $65 respectively.

The company has filed for more than 40 patents to protect their intellectual property, which Merrell said has been one of their key challenges. She also described the manufacturing, logistic, and financing challenges faced by a small start-up. LLF's path to market will not focus on direct sales to consumers; instead they will utilize traditional channels such as lighting agents, national homebuilders, architects, engineers, designers, and electricians.

Merrell concluded by sharing her vision of how LED lighting will change the lighting industry, comparing the traditional lighting model with the LED lighting model. "Whoever is making the fixture will *be* the industry," Merrell concluded.

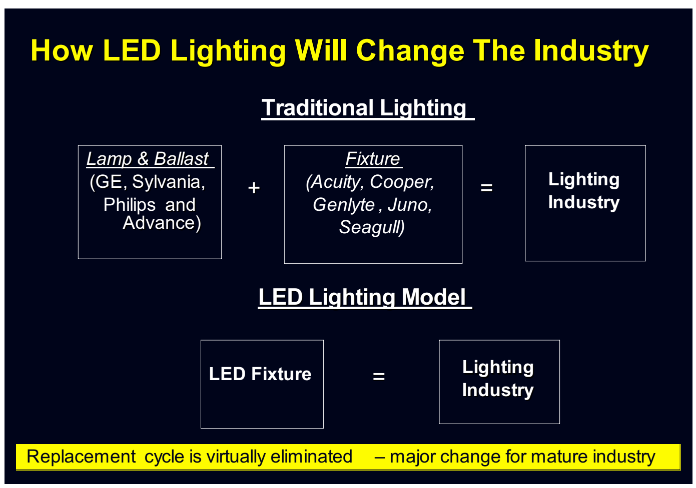


Figure 2-2: How LED Lighting Will Change the Industry

2.6 SSL Partnership—How Does the Alliance Participate in Getting SSL to Market?

Kevin Dowling, Next Generation Lighting Industry Alliance

Kevin Dowling, Chair of the Next Generation Lighting Alliance (NGLIA), gave a presentation explaining how the Alliance participates in getting solid-state lighting to the market. NGLIA is an alliance of for-profit corporations formed to accelerate solid-state lighting development and commercialization through government-industry partnership. In 2005, DOE and NGLIA signed a Memorandum of Agreement (MOA) designed to enhance the manufacturing and commercialization focus of the DOE SSL program and enable DOE to access the expertise of this organization of lighting manufacturers.

The Alliance currently has 14 members, including 3M, Acuity Brands Lighting, Air Products & Chemicals, Inc., CAO Group Inc., Color Kinetics Incorporated, Corning, Inc., Cree Inc., Dow Corning Corporation, Eastman Kodak Company, General Electric Company, GELcore LLC, Light Prescriptions Innovators LLC, Osram Sylvania Inc., and Philips Electronics North America Corporation.

The Alliance supports energy bill directives, identifying SSL technology needs from an industry perspective and assessing the progress of SSL research activities. In addition, it supports the DOE SSL Commercialization Plan, providing input for DOE reports, draft ENERGY STAR specifications, and design competition such as Lighting for Tomorrow. The Alliance also supports communications and outreach activities to bring the message of SSL technology and potential energy savings to the government, and provide a forum for SSL communication among for-profit companies.

Dowling concluded by encouraging interested companies to join the Alliance to "help steer the SSL field, accelerate commercialization, and partner with our government." For information on joining the Alliance, visit the NGLIA website at: www.nglia.org.

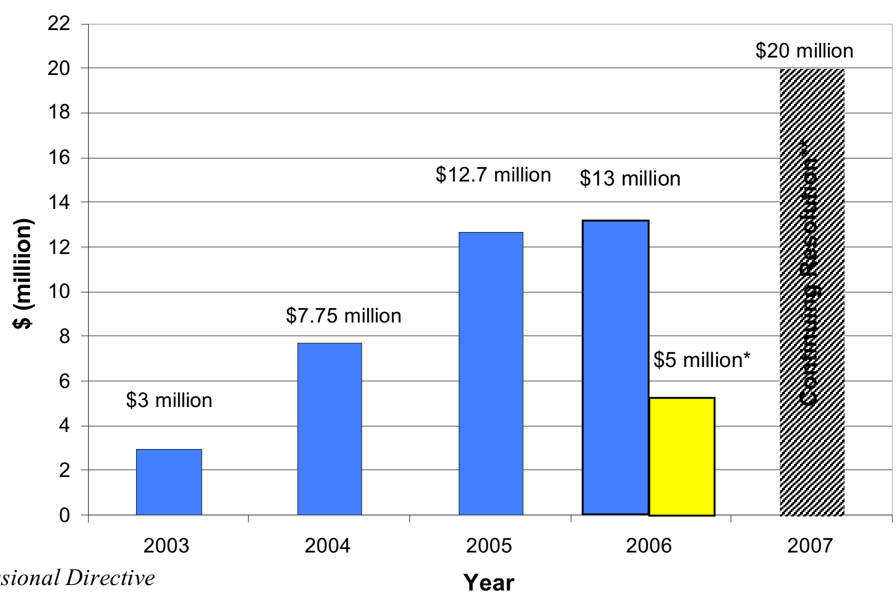
3. DOE Solid-State Lighting Research and Development

At the 2007 Workshop, DOE offered an overview of the DOE SSL R&D program, including presentations on DOE-funded SSL R&D, an overview of the Basic Energy Sciences program research areas related to SSL, and guidance on preparing a comprehensive application for DOE funding.

3.1 DOE SSL R&D Program Update

James Brodrick, U.S. Department of Energy

James Brodrick delivered an overview of the DOE SSL R&D Program, detailing the program mission, budget, and current areas of focus. The 5-year-old program to date has invested $92 million dollars in research and development grants distributed among 64 projects, with approximately 20% of that investment coming from the researchers as cost-share. In the last five years, 64 patents have been filed as a result of DOE-funded research. For more information on SSL patents resulting from DOE-funded research, download the SSL patents handout at: http://www.netl.doe.gov/ssl/materials_2007.html.



*Congressional Directive
**Congressional Budget is not yet approved

Figure 3-1: Congressional SSL Appropriation ($ million)

The total portfolio value is divided into 28 OLED projects for $39.9 million, and 36 LED projects receiving $51.8 million. The Department funds solid-state lighting research in partnership with industry (31% to large corporations, 29% to small businesses), universities (21%), and national labs (19%). Brodrick provided further breakdown, indicating that funding for 52 Core Technology projects equals $62.9 million; 12 Product Development projects are funded by $28.9 million.

A closer look at the 29 LED Core Technology projects reveals that 19 involve research with Gallium Nitride (GaN) materials systems, 3 are researching phosphors, 2 are studying other compound semiconductors, and 5 involve work with other material systems.

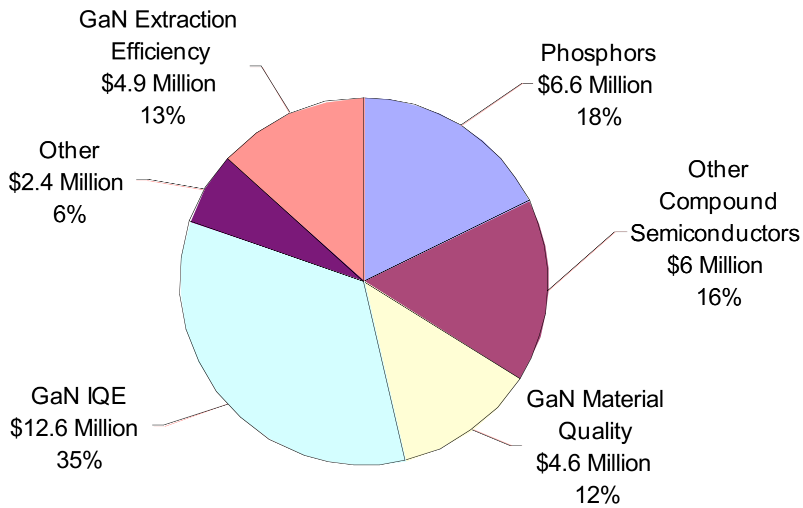


Figure 3-2: LED Core Research ($37.1M)

Of the 23 OLED Core Technology projects, 4 are studying general OLEDs, 4 are researching small molecule OLEDs, 5 are researching transparent conductive oxides, 1 is researching polymer OLEDs, and 9 are researching other areas.

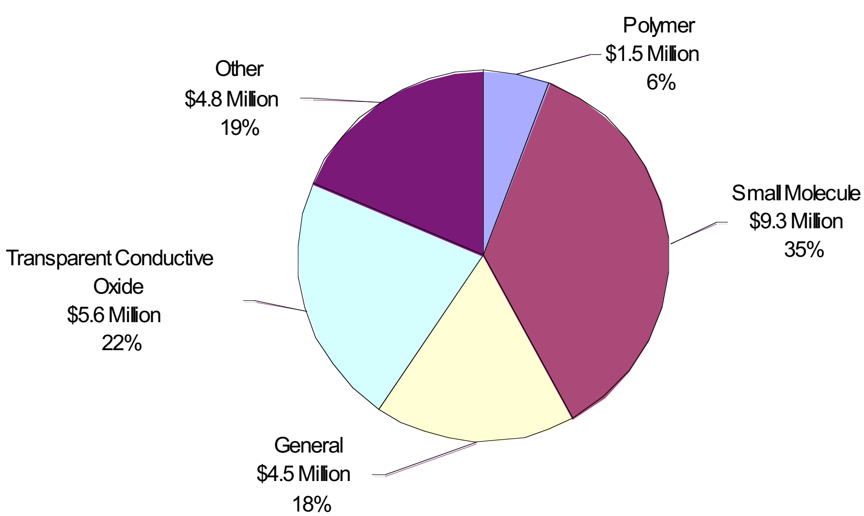


Figure 3-3: OLED Core Research ($25.7M)

Brodrick concluded by recognizing five project teams for their significant achievements in 2006:

- **Pacific Northwest National Laboratory**: The team at PNNL created a blue OLED device with an external quantum efficiency of 11% at 800 cd/m^2. Their new molecular structure enables use of blue organic phosphors at low operating voltage.
- **University of Southern California:** USC researchers developed a new OLED device that employs a novel combination of blue fluorescent and red and green phosphorescent dopants to produce an OLED with an efficacy of 24 lm/W.
- **Universal Display Corporation**: The UDC team improved the light extraction of white phosphorescent OLEDs using microlens arrays and aperiodic gratings, resulting in efficacy values of 30 lm/W at 70 CRI, and a record external quantum efficiency of 30%.
- **Technologies and Devices International:** TDI developed novel low-defect GaN template substrates and InN epitaxial wafers, used for fundamental research, product development, and production of high efficiency, high brightness LEDs.
- **Cree Inc:** Cree released the new XLamp® 7090, setting new records for LED brightness and efficacy of 85 lm/W. The new XLamp is the first product to utilize the new Cree EZBright chip, also developed with DOE R&D funding support.

DOE recognized five project teams for their significant R&D achievements in 2006. Pictured, left to right: Linda Sapochak, Paul Burrows, Pacific Northwest National Laboratory; Mark Thompson, University of Southern California; Monica Hansen, Cree Inc.; Brian D'Andrade, Universal Display Corporation; Alexander Usikov, Technologies and Devices International; James Brodrick, DOE.

3.2. Reports on DOE-Funded SSL R&D Projects

The Phoenix Workshop also included brief presentations on current DOE-funded SSL R&D projects. Presenters for each of the current projects provided an overview of the project team, R&D objectives, project elements, and technology. The presentations provided attendees with a snapshot of DOE's current project portfolio and progress.

For an overview of all current DOE-funded SSL R&D projects, including a brief description, partners, funding level, and proposed timeline, see the 2007 SSL Project Portfolio in the Publications section of the DOE SSL website at: http://www.netl.doe.gov/ssl/materials_2007.html.

List of SSL R&D Project Presentations

Novel Approaches to High-Efficiency III-V Nitride Heterostructure Emitters for Next-Generation Lighting Applications
Georgia Tech Research Corporation
Russell Dupuis

Ultrahigh Efficiency Microcavity Photonic Crystal LEDs
Sandia National Laboratories
Arthur J. Fischer

Low-Cost Blue/UV LEDs with Very High Photon Conversion and Extraction Efficiency for White Lighting
Boston University
Theodore Moustakas

Nanostructured High-Performance Ultraviolet and Blue Light Emitting Diodes for solid-state Lighting
Brown University
Arto Nurmikko

Development of White-Light Emitting Active Layers in Nitride-Based Heterostructures for Phosphorless Solid State Lighting
University of California, San Diego
Kailash Mishra

High-Efficiency LED Lamp for Solid State Lighting
Cree Inc. Santa Barbara Technology Center
Monica Hansen

Small-Area Array-Based LED Luminaire Design
Cree Inc. Santa Barbara Technology Center
Monica Hansen

An Efficient LED System-in-Module for General Lighting Applications
Phillips Light Electronics
Jim Gaines

Scaling Up: KiloLumen Solid-State Lighting Exceeding 100 LPW via Remote Phosphor
Light Prescriptions Innovators LLC
Waqidi Falicoff

Highly Recombination Efficiency White Phosphorescent Organic Light Emitting Diodes
Universal Display Corporation
Brian D'Andrade

High-Efficiency, Illumination Quality OLEDs for Lighting
GE Global Research
Joseph Shiang

Novel Organic Molecules for High Efficiency Blue Organic Electroluminescence
Pacific Northwest National Laboratory
Dr. Paul E Burrows

Novel Materials for High-Efficiency White Phosphorescent OLEDs
University of Southern California
Mark Thompson

Surface Plasmon Enhanced Phosphorescent Organic Light Emitting Diodes
University of California Santa Barbara
Alexander Mikhailovsky

Enhancing Change Injection and Device Integrity in Organic LEDs
Agiltron Inc.
Dr. King Wang

Novel Low-Cost Organic Vapor Jet Printing of Striped High Efficiency Phosphorescent OLEDs for White Lighting
Universal Display Corporation
Teddy Zhou

Material and Device Designs for Practical Organic Lighting
Los Alamos National Laboratory
Brian Crone

Zinc Oxide Light-Emitting Diodes
Materials Modification, Inc.
Jim Intrater

Low Cost Packaging Solutions for High-Efficiency OLED Lighting
Dow Corning Corporation
Wm. Ken Weidner

Improved InGaN Epitaxy Yield by Precise Temperature Measurement
Sandia National Laboratories
J. Randall Creighton

A Novel Growth Technique for Large Diameter AlN Single Crystals
Fairfield Crystal Technology, LLC
Shaoping Wang

ZnO PN Junctions for Highly Efficient, Low-Cost Light Emitting Diodes
University of Florida
David Norton

Development of Advanced Phosphors by Spray Based Processes for Solid-State Lighting
Cabot Corporation
Liam Noailles

Nanocomposite Down-Converting System for SSWL, Phase II
Nanosys Inc.
Jian Chen

Phosphor-Free Solid-State Light Sources
Cermet Inc.
Jeff E. Nause

Novel Low Cost Technology for SSL
Technologies and Devices International, Inc.
Alexander Usikov

3.3. Poster Session for First-Year Projects

In the evening, a Poster Session and Reception for first-year DOE SSL projects provided additional opportunities to share research results, identify needs, and build relationships. The following list details the poster topics and presenters. For more detailed information on the first-year projects, see the 2007 SSL Project Portfolio at http://www.netl.doe.gov/ssl/materials_2007.html.

Teddy Zhou (left) of Universal Display Corporation and David Geohegan (right) of Oak Ridge National Laboratory, take the opportunity to discuss first-year DOE SSL R&D projects at an evening Poster Session and Reception.

Catalog of Posters for First-Year Projects

Photoluminescent Nanofibers for High Efficiency Solid-State Lighting
RTI International
Lynn Davis

Investigation of Surface Plasmon Mediated Emission from InGaN LEDs Using Nano-patterned Films
Sandia National Laboratories
Arthur Fischer

Novel Plastic Substrates for Very High Efficiency OLED Lighting
Universal Display Corporation
Brian W. D'Andrade

Novel High Efficiency High CRI Phosphorescent OLED Lighting Containing Two Broad Emitters
Universal Display Corporation
Brian W. D'Andrade

High Quality Low Cost TCOs
Los Alamos National Laboratory
Anthony Burrell

Innovative Strain Engineered InGaN Materials of High Efficiency Green Light Emission
Sandia National Laboratories
Michael Coltrin

Hybrid Nanoparticle/Organic Semiconductors for Efficient Solid-State Lighting
Los Alamos National Laboratory
Darryl Smith

Transparent Electrodes for Highly Efficient OLED Lighting
Oak Ridge National Laboratory
David Geohegan

White LED with High Package Extraction Efficiency
Osram Sylvania Development Inc.
Yi Zheng & Matt Stough

Ultra High p-doping Materials Research for GaN Based Light Emitters
Technologies and Devices International, Inc.
Vladimir Dmitriev

An Integrated Solid-State LED Luminaries for General Lighting
Color Kinetics Incorporated
Kevin Dowling

Microporous Alumina Confined Nanowire Inorganic Phosphor Film for Solid-State Lighting
Physical Optics Corporation
Alexander Parfenov

High Efficiency Nitride Based Photonic Crystal Light Sources
University of California, Santa Barbara
Jim Speck

Highly Efficient Organic Light-Emitting Devices for General Illumination
Physical Optics Corporation
Paul Shnitser

OLED Lighting Device Architecture
Eastman Kodak Company
Yuan-Sheng Tyan

Low Cost Transparent Conducting Nanoparticle Networks for OLED Electrodes
Argonne National Laboratory
Jeffrey W. Elam

Epitaxial Growth of GaN Based LED Structures on Sacrificial Substrates
Georgia Institute of Technology
Ian Ferguson

Phosphor Systems for Illumination Quality Solid State Lighting Products
General Electric Global Research
James Healy

Quantum Dot LED
Eastman Kodak Company
Keith Kahen

Nanostructural Engineering of Nitride Nucleation Layers for GaN Substrate Dislocation Reduction
Sandia National Laboratories
Daniel D. Koleske

Novel ScGaN and YGaN Alloys for High Efficiency Light Emitters
Sandia National Laboratories
Daniel D. Koleske

High Efficiency Long Lifetime OLEDs with Stable Cathode Nanostructure
Los Alamos National Laboratory
Samuel S. Mao

Advanced Materials for Thermal Management in III-Nitride LEDS
k Technology Corporation
Mark J. Montesano

Multi-faceted Scientific Strategies Toward Better SSL of Phosphorescent OLEDs
University of North Texas
Mohammad Omary

Novel High Work Function TCO for OSSL Using Combinatorial Techniques
Pacific Northwest National Laboratory/ National Renewable Energy Laboratory
Paul Burrows & David Ginley

Development of White LEDs Using Nanophosphor-InP Blends
Sandia National Laboratories
Lauren Shea Rohwer

Low-cost Substrates for High Performance Nanorod Array LEDs
Purdue University
Timothy D. Sands

Cavity Light Emitting Diode for Durable, High Brightness and High-Efficiency Lighting Applications
SRI International
Yijian Shi

High Efficiency OLED Devices for Solid-State Lighting
University of Florida
Franky So

Development of Bulk GaN Growth Technique for Low Defect Density Large Area Native Subs
Sandia National Laboratories
Karen Waldrip

Nanowire Templated Lateral Epitaxial Growth of Low Dislocation Density GaN
Sandia National Laboratories
George T. Wang

Next Generation Hole Injection/Transport Nano-Composites for High Efficiency OLED Development
Agiltron Inc.
King Wang

High Performance Green LEDs by Homoepitaxial MOVPE
Rensselaer Polytechnic Institute
Christian Wetzel

3.4. Basic Energy Sciences (BES) Program Update

Tim Fitzsimmons, U.S. Department of Energy, Basic Energy Sciences Program

Tim Fitzsimmons from DOE's Office of Science, Basic Energy Sciences (BES) program, presented the BES update entitled "Fundamentals at the Nanoscale." "While the recent progress in SSL efficiency is important," Fitzsimmons said by way of introduction, "it is dwarfed by the chasm that needs to be crossed."

To define the challenges to be met and lay the groundwork for a plan of attack, the BES group held a two-day meeting in Bethesda, Maryland, in May 2006 to discuss "Basic Research Needs for SSL." Participants formed three panels devoted to LED science, OLED science, and Crosscutting science. Each panel developed and presented a list of research priorities.

The BES group as a whole defined two Grand Challenges and associated priority research directions:

Grand Challenge 1: Rational design of solid-state lighting structures
Grand Challenge 2: Control of radiative and nonradiative processes in light-emitting materials

For more detailed information on the research priorities identified at the BES workshop, see the workshop report at: http://www.sc.doe.gov/bes/reports/list.html.

Fitzsimmons emphasized that BES National User Facilities for nanoscale science are available for the use of all researchers with projects emphasizing fundamental research in SSL materials and devices. A general BES call for proposals is made each year around October 1, and can be accessed on the BES website at: http://www.sc.doe.gov/bes/bes.html.

In closing, Fitzsimmons again emphasized the need for breakthrough research results to meet DOE's SSL goals: "Extrapolations of current technologies will not get us to the goals of SSL," he stated.

3.5. DOE SSL Funding Opportunities—Preparing a Comprehensive Application

C. Edward Christy, National Energy Technology Laboratory

Eddie Christy from the National Energy Technology Laboratory presented an overview of the DOE SSL proposal review process and offered insights on preparing a comprehensive application. Christy began by detailing the proposal review process. Each proposal is initially reviewed by a member of the DOE Procurement staff, and then sent to three technical reviewers. The technical reviewers have two weeks to evaluate the technical merit of the proposal, assign a score, and detail its strengths and weaknesses. Next, the Merit Review Committee looks at all the proposals and sets a range of technically acceptable scores, after which the selection official—a high level DOE manager—decides on the funding. A debriefing letter is sent to all applicants, informing them of the strengths and weaknesses of their proposal for future use.

Christy then offered common-sense guidance on preparing a comprehensive application. The application must be submitted on time and complete, with all budget and technical details addressed. Also, the proposal “needs to be a good idea that is responsive to an SSL need identified in the solicitation areas of interest,” Christy stated.

The Background section must clearly present a thorough work plan with an explanation on how the proposed path is better that what currently exists and addresses DOE targets. It should also include a thorough description of preliminary work in the field already performed by the research team. The Statement of Project Objectives should indicate how the proposed research will result in a leap forward in SSL technology. “DOE can’t afford to fund marginal improvements,” Christy said. The Milestones should be qualitative, quantitative, and realistic.

In describing the team that will carry out the proposed research, Christy said to be sure that all personnel are qualified for their part of the project and can commit significant time to the effort. The availability of the necessary facilities and equipment should be clearly outlined. Finally, the proposal must show DOE that you have a commercialization strategy for the proposed technology or product.

In conclusion, Christy emphasized the importance of reading the complete solicitation document; proposals with missing elements may not be reviewed, or may receive a low rating and not be selected. He advised potential applicants to address all technical evaluation criteria; to ask questions via the method described in the solicitation; and not to wait until the last minute to submit the applications, as deadlines are strictly enforced. “Remember, you are trying to tell a story,” Christy stated. “You are trying to convince the reviewers that you know what you are talking about.”

4. Designing SSL for Market

4.1 Lighting for Tomorrow Competition

Kelly Gordon, Pacific Northwest National Laboratory

Kelly Gordon of Pacific Northwest National Laboratory presented the winners of the 2006 Lighting for Tomorrow SSL Competition. Organized by the American Lighting Association, the Consortium for Energy Efficiency, and DOE, Lighting for Tomorrow began in 2003 with the goals of (1) encouraging and recognizing attractive, energy-efficient residential lighting fixtures, and (2) building demand for energy-efficient lighting. The first three years of the competition focused on fluorescent lighting; the 2006 competition was the first to include a category for LED products.

The rules stated that the products submitted must be for general illumination only, and must address niche applications such as under-cabinet and in-cabinet lighting, desk and task lighting, and outdoor (porch, step, and path) lighting. Thirty products were entered, and the four winning fixtures, shown below, were displayed at the Phoenix Workshop.

Diode 28 by American Fluorescent
5 watt under-cabinet device

Linear by Lucere Lighting
18 watt under-cabinet device

Halley by Lucesco
19 watt, dimmable, portable
desk/floor task light

Lakeland by Progress Lighting
3.5 watt, family of outdoor fixtures

Honorable mentions were awarded to:

- LED Bullet by American Lighting LLC (in-cabinet luminaire)
- HF2Eye by Osram Sylvania (in-cabinet luminaire)
- Javelin by Albeo (moveable, individually controlled, replaceable LED modules)
- Luxrail by io Lighting (an under-handrail stair luminaire).

Gordon also provided a preview of plans for the 2007 Lighting for Tomorrow competition. Once again, there will be one competition with two categories: CFL fixture families and LED-based fixtures. The LED-based fixture category will again focus on niche applications such as under-cabinet, portable desk/task, outdoor porch/path/step, and recessed downlights (new this year), plus a new "Cutting Edge" design category.

Judging criteria will be based on quality, application efficiency, thermal management, and aesthetic appearance. Bonus points will be awarded in 2007 for innovative designs that take advantage of unique LED attributes and those that have no off-state power consumption.

Participants entering niche devices must submit a prototype or production luminaire, while the "Cutting Edge" participants may submit a prototype, production luminaire, or working model of their design. The timeline is:

- March 31, 2007—notification of Intent to Submit
- May 31, 2007—entries due
- June-July, 2007—judging
- September 9, 2007—announcement of winners

For more information on the time line, rules, and entry requirements, visit: www.lightingfortomorrow.com.

4.2 What Architects and Designers Want from SSL

Dawn Hollingsworth, Visual Terrain

Lighting Consultant Dawn Hollingsworth of Visual Terrain quickly and concisely summarized what she and other designers are looking for from SSL. They want it to solve lighting application challenges, create interesting environments, provide energy savings, and provide cost/benefit value to clients. What's more, Hollingsworth said, "We want it all now."

Hollingsworth sees SSL as one tool in a large toolbox that lighting designers use, citing the following advantages:

- **Size:** the small size of LEDs allows her to "tuck them anywhere."
- **Color changing ability:** Offers flexibility in design.
- **Life:** Though she doesn't believe claims that LEDs can last 100,000 hours, Hollingsworth is encouraged that they last much longer than other lighting technologies.
- **Lack of direct heat from the source**: Low device temperatures make them usable in areas where people might touch them.
- **Energy savings:** This is a big selling point for her clients.

On the negative side, Hollingsworth pointed out a number of problems that impede widespread use of SSL by lighting designers. These include:

- Poor color rendering with white LEDs (too cold, too blue)
- Lack of consistency among manufacturers regarding color
- Very large drivers required to provide heat sinking for higher output products
- High cost
- Technology confusion for the buyer
- Lack of industry standardization
- Additional costs for control circuitry such as dimmers
- Replacement costs and availability (designers are afraid they won't be able to get the same product again when the time comes for replacement)

Key product issues include the lack of full disclosure regarding power and efficiency; driver inefficiencies (including energy code conflicts); and lack of architectural integration or proper electrical connections.

In summary, Hollingsworth said that the lighting design community and engineering companies must communicate their needs and capabilities more clearly. “We need to build bridges” between our disciplines, she said.

5. Guiding Market Introduction of Energy-Efficient Solid-State Lighting Products

The 2007 DOE SSL Workshop concluded with a series of presentations focused on guiding successful market introduction of energy-saving SSL products. Gregg Ander from Southern California Edison, Marc Ledbetter from Pacific Northwest National Laboratory, and James Brodrick from DOE shared insights, lessons learned, and strategies for moving SSL to market. Brodrick concluded by stressing the multiple ways to partner and participate with DOE, and announced an upcoming DOE workshop in April focused specifically on market introduction issues and opportunities. For more information about the upcoming workshop, see: http://www.netl.doe.gov/ssl/PasadenaWorkshop.html.

Left to Right: Gregg Ander (Southern California Edison), Marc Ledbetter (Pacific Northwest National Laboratory), and James Brodrick (DOE) shared insights, lessons learned, and strategies for moving SSL to market.

5.1 Solid-State Lighting: Energy Efficiency Portfolio Opportunities
Gregg Ander, Southern California Edison

Gregg Ander from Southern California Edison addressed workshop attendees with a talk focused on the theme "What Are You Doing to Keep the Lights On?" New energy policies and regulations in California establish a framework for energy-efficiency opportunities, and new lighting technologies like SSL will play a critical role in meeting aggressive energy and demand reduction goals.

To meet growing energy needs through 2013, 50-60% of the demand will have to be supplied through improvements in energy efficiency. Ander estimates that approximately 50% of the potential energy efficiency savings in the commercial sector will come from interior lighting applications. But he noted that market intelligence for pre-commercial or new innovations is frequently lacking.

Ander shared the California Public Goods Charge (PGC) Model of Product Commercialization (see Figure 5-1), noting that it often takes decades for commercial acceptance of new building technologies to take hold, because the building industry is so diffuse. After the early adopters of a new technology are exhausted, there is a chasm in the commercial acceptance curve that is frequently called, 'The Valley of Death." "If it doesn't cross this chasm," as Ander put it, "the product can die." Successful products eventually have building codes developed to support their use, and then the cycle starts over again with newer technologies.

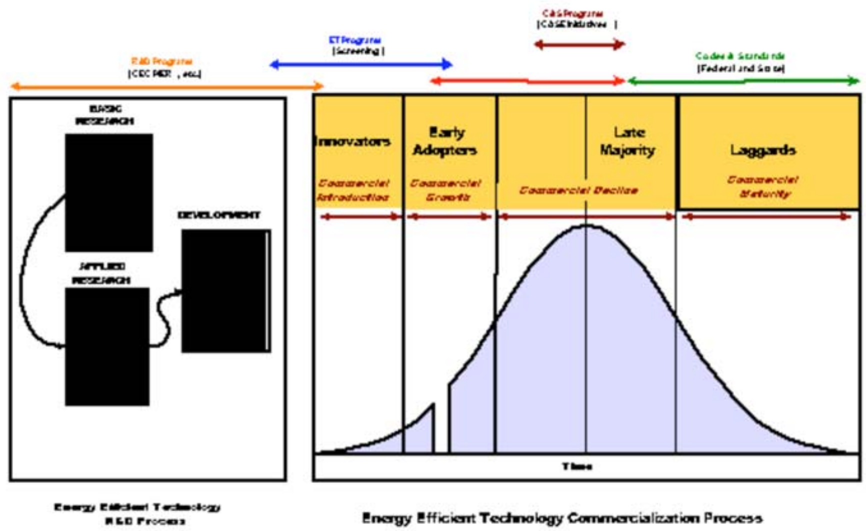


Figure 5-1: California PGC Model of Product Commercialization

Ander emphasized that solid-state lighting technologies offer a wide range of possibilities in home, office, and retail applications. Southern California Edison is currently assessing a number of SSL technologies, including:

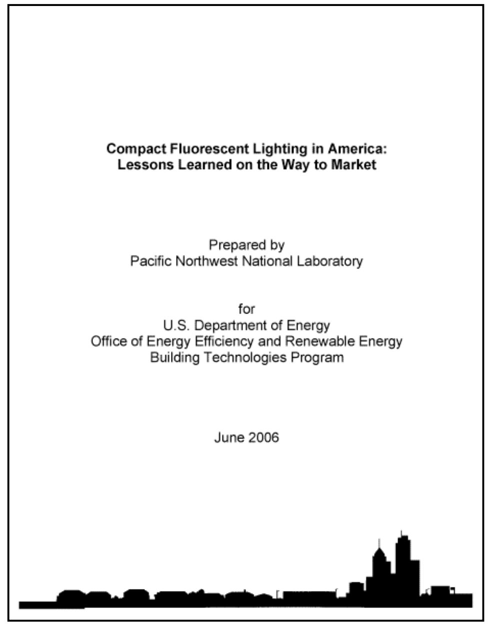
- "OPEN" or "CLOSED" lights for retail stores
- Downlights for residential applications
- Reach-in refrigerated display-case lighting for supermarkets
- LED hybrid porch lights and pathway lights for residences and communities
- LED taxiway lighting for airport runways

Southern California Edison has its own demonstration and testing laboratory, including a built-in kitchen equipped with SSL, fluorescent, and incandescent lights to enable easy comparison of various technologies in different scenarios. Ander emphasized the necessity of uniformity in SSL light output by relating an example: if builders are shown a lineup of ten SSL luminaires with different color characteristics, they will shy away from the technology because they cannot afford callbacks.

Finally, Ander related several case studies that demonstrate growing acceptance of LED lighting, including the use of LED taxiway lighting that replaced 42 watts of incandescent lighting with 6 watts dimmable LED lighting to accommodate taxiway modulation requirements, and SSL streetlights that are close to being able to replace sodium discharge lamps.

5.2 DOE's SSL Commercialization Support

Marc Ledbetter, Pacific Northwest National Laboratory



Compact Fluorescent Lighting in America:
Lessons Learned on the Way to Market

Prepared by
Pacific Northwest National Laboratory

for
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Building Technologies Program

June 2006

Marc Ledbetter of Pacific Northwest National Laboratory (PNNL) presented an overview of DOE's Commercialization Support Plan. He began by sharing key findings from the DOE report, *Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market.* To download a PDF copy of the report, see: http://www.netl.doe.gov/ssl/publications.html.

Early CFLs were big and heavy, with poor color quality and high prices. Early marketing mistakes included exaggerated lifetime and incandescent equivalency claims. Lack of a common product name hindered consumer awareness, and early CFLs were not available in supermarkets where consumers were used to buying replacement bulbs. Untrained retailers did not understand the product and could not answer consumer questions. According to Ledbetter, the key take-away message is that early consumer experience with CFLs still defines the public's attitude toward the product, even though CFL technology and marketing strategies have much improved.

Ledbetter cited several key lessons learned that apply to market introduction of SSL:

- **Know and admit technology limitations.** Manufacturers should avoid exaggerated or inconsistent claims for lifetime and incandescent equivalency, and direct consumers away from inappropriate lighting applications.
- **Establish minimum performance requirements.** Manufacturers and energy efficiency groups should coordinate to establish minimum performance requirements. The wide disparity of CFL specifications caused confusion and complication.
- **Work toward consistent, industry-wide terminology.** Again, manufacturers and efficiency groups should work together to identify and avoid terms with negative connotations (e.g., "fluorescent").

Ledbetter then provided an overview of DOE's commercialization support plan, designed to focus DOE resources on strategic areas to move the SSL market toward the highest energy efficiency and the highest lighting quality. DOE's plan draws on key partnerships with the SSL industry, standards setting organizations, energy efficiency groups, utilities, and others, as well as lessons learned from the past. Commercialization support activities are closely coordinated with research progress to ensure appropriate application of SSL products, and avoid buyer dissatisfaction and delay of market development.

Key elements of the plan include:

- **Technical information –** To provide accurate, unbiased information for users/buyers, DOE has developed a series of technical fact sheets focused on critical issues such as color quality, lifetime, and thermal management. These fact sheets are available for download at: http://www.netl.doe.gov/ssl/publications.html. In addition, DOE's SSL Technical Information Network will initiate in 2007. The network will share information and materials through existing efficiency programs and communications channels to increase awareness of SSL technology, performance, and appropriate applications.
- **Product testing –** DOE's SSL Commercial Product Testing Program provides unbiased information on the performance of commercially-available SSL products. Test results can be requested on the DOE SSL website at: http://www.netl.doe.gov/ssl/comm_testing.htm.
- **Technology demonstrations –** DOE is planning SSL technology demonstration venues to provide real-life experience and data on energy consumption, light output, color consistency, and interface/control issues. Additional SSL technology demonstrations will include the 2007 Solar Decathlon and the DOE Showcase.
- **Technical support for standards –** DOE provides leadership and support to accelerate the standards development process, facilitating ongoing collaboration among standards setting organizations and offering technical assistance in the development of new standards.
- **ENERGY STAR –** DOE ENERGY STAR specifications for SSL products will set minimum requirements for earning the ENERGY STAR label, and guide buyers to select cost-effective, energy-efficient SSL products. DOE issued draft specifications in December 2006; final criteria will be issued in April 2007.
- **Design competitions –** In partnership with the American Lighting Association and the Consortium for Energy Efficiency, DOE sponsors Lighting for Tomorrow, a design competition that encourages and recognizes excellence in design of energy-efficient residential light fixtures.

5.3. ENERGY STAR® Criteria Update

James Brodrick, U.S. Department of Energy

James Brodrick, speaking for Richard Karney, DOE ENERGY STAR Product Manager, presented an update on DOE's ENERGY STAR program for SSL products. In December 2006, DOE issued draft criteria for SSL luminaires intended for general illumination.

The draft document proposed two categories for SSL technologies based on (A) near-term niche applications, and (B) future efficacy targets, determined as technology improves. The two-category approach will maintain the integrity of the ENERGY STAR label by taking advantage of near-term appropriate applications while planning for future performance levels that exceed the efficacy of today's best CFLs. The two-category approach also allows time for related standard and test procedure development. The intention is to eventually drop category A when there are a large number of products in Category B.

In 2006, DOE hosted two standards workshops to convene key standards setting organizations, including the Illuminating Engineering Society of North America (IESNA), National Institute of Standards and Technology (NIST), National Electrical Manufacturers Association (NEMA), American National Standards Institute (ANSI), Underwriters Laboratories (UL), International Electrotechnical Commission (IEC), International Commission on Illumination (CIE), and Canadian Standards Association (CSA). These organizations agreed to work in parallel with the ENERGY STAR schedule; DOE provides ongoing technical assistance in the development of new standards. In May 2007, final procedures are expected for photometric measurements (IESNA LM-79); lumen depreciation (IESNA LM-80); chromaticity (ANSI C78.377A); electrical measurements (ANSI C78.XX3); and definitions (RP-16).

The DOE ENERGY STAR criteria focus on luminaire efficacy as the key metric, based on the new LM-79 test procedure in process. Category A niche applications include undercabinet kitchen, undercabinet shelf-mounted task, portable desk/task, outdoor wall-mounted porch, outdoor step, outdoor pathway, and recessed downlights. The ENERGY STAR criteria will continue to evolve to keep pace with technology advances, and DOE may add additional Category A niche applications as technology improves.

Brodrick concluded by outlining the schedule for the ENERGY STAR criteria development:

- December 2006 – Draft criteria issued
- February 2007 – Stakeholder meeting to discuss draft criteria
- April 2007 – Final criteria issued
- December 200 – Effective date

For more information on DOE ENERGY STAR for SSL, see http://www.netl.doe.gov/ssl/energy_star.html.

6. Research and Development Priorities—Breakout Sessions

One afternoon of the SSL Workshop was dedicated to detailed discussion on the Department's SSL R&D priority tasks. Five concurrent breakout sessions were convened – three on LEDs (with ~40 people in each) and two on OLEDs (with ~30 people in each). DOE scheduled these breakout session discussions in order to solicit input from the workshop participants on the selection of priority tasks for R&D funding for the next one to two years.

All workshop participants had been given a draft copy of the 2007 Edition of the SSL Multi-Year Program R&D technical chapter. Within the draft chapter, proposed updates to the SSL Funding Priority Task Lists were identified, based on input from the NGLIA expert team guidance. The priority list represents those tasks which DOE intends to consider foremost when allocating SSL R&D funding. Participants were given an opportunity through these breakout group discussions to review the revised priorities and propose modifications or amendments to the draft NGLIA list.

Unlike previous meetings, the breakout sessions did not strictly 'vote' on individual tasks, but rather discussed issues and occasionally took a roll-call so as to capture a general feel for the groups' opinion on a topic. All five breakout groups were asked to conduct concurrent reviews on their respective Core Technology and Product Development R&D priorities. All of the ideas, issues and topics discussed in each of the five breakout groups are captured in this chapter of the workshop report, grouping the discussion into LEDs and OLEDs.

The Department's approach for engaging participants in the prioritization process proceeded as follows:

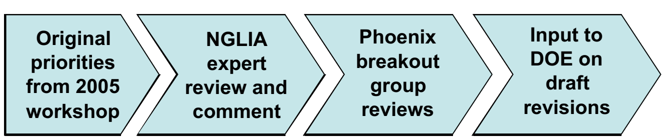


Figure 6-1: Linear Representation of SSL R&D Tasks Discussion and Prioritization

The Department's review of its SSL R&D priorities began several months before the Phoenix workshop in a series of technical conference calls with the NGLIA. Through these calls, a set of proposed revisions were compiled, representing the recommended changes from the NGLIA technical experts. This proposal was then circulated to all the stakeholders attending the Phoenix workshop, as well as being posted on the DOE website for general public review. In the breakout sessions in Phoenix, participants focused on reviewing these changes, and identifying any areas where they felt further revisions were necessary. The output from all the breakout groups was combined and provided to DOE as overall guidance for finalizing the SSL R&D priorities over the next one to two years. The final priorities as determined by the DOE will be included in an update to the technical chapter of the MYPP to be available in April.

Each of the five breakout groups was given the same general charge, centered around four critical steps:

- Review the draft priorities proposed by the NGLIA Team
- Suggest additional candidate subtasks for the priority lists
- Suggest deleting subtasks from the priority lists
- Modify or suggest new metrics / target values for the tasks

The following sections of this chapter summarize the discussion in the breakout groups pertaining to the R&D priority task list. The discussion summary is organized to be consistent with DOE's R&D portfolio, 1) Inorganic Core Technology, 2) Inorganic Product Development, 3) Organic Core Technology and finally 4) Organic Product Development. Under each subtask heading is a graphic summary including the title and a short descriptor of the subtask and the NGLIA recommendations as to priority, metrics, targets, and status. In Appendix C and in the following discussion, these subtasks are identified as "high priority," meaning they are considered the Department's highest SSL R&D priorities for the next 1-2 years. Some subtasks are identified as "medium priority," meaning they are expected to be the next group of high priorities, but are not yet ready to be funded.

6.1 Subtask Priority Lists

The following list shows the recommended "high priority" subtasks as given by the NGLIA before the workshop. These and the medium priority tasks were the main topics of discussion during the breakout groups.

Inorganic Core Technology Subtask Priority List

1.1.2 High-efficiency semiconductor materials
1.1.3 Reliability and defect physics for improved emitter lifetime and efficiency
1.2.1 Device approaches, structures and systems
1.2.2 Strategies for improved light extraction and manipulation
1.3.1 Phosphors and conversion materials

Inorganic Product Development Subtask Priority List

2.1.2 High-efficiency semiconductor materials
2.2.1 Manufactured materials
2.2.3 Electronics development

2.3.1 Optical coupling and modeling
2.3.4 Thermal design
2.3.6 Evaluate luminaires lifetime and performance characteristics

Organic Core Technology Subtask Priority List
3.1.2, 3.2.2 High-efficiency, low-voltage, stable materials and approaches to OLED structures between the electrodes for improved-performance low-cost white-light devices
3.2.1 Strategies for improved light extraction and manipulation
3.2.3 Research on low-cost transparent electrodes
3.4.2 Investigation of low-cost fabrication and patterning techniques and tools

Organic Product Development Subtask Priority List
4.1.1 Low-cost substrates
4.1.2, 4.2.2 Between electrodes high-efficiency, low-voltage materials and architectures that improve device robustness, increase lifetime.
4.2.1 Implementing strategies for improved light extraction and manipulation
4.3.1 OLED encapsulation packaging for lighting applications
4.4.1 Module and process optimization and manufacturing

6.2 Inorganic Core Technology Subtask Discussion

Task 1.1 Inorganic Materials Research
Goal: increase internal quantum efficiency

1.1.1 Large Area Substrates, buffer layers, and wafer research		**Medium Priority**
Short Descriptor: *Create efficient broadband semi-conducting materials. Develop lower defect density materials (GaN, ZnO, substrates).*		
Metric	**2006**	**Program Target (2015)**
• Defect density • Wavelength variation across wafer		$< 10^5$ per cm^2 $\sigma = 1nm$

Priority:
One of the suggestions from the NGLIA review was to move Subtask 1.1.1 from high priority to medium priority. All the LED breakout groups had some discussion on this subtask. One group discussed the fact that there is a big difference in the performance between gallium nitrate (GaN) and zinc oxide (ZnO). An individual in this group asserted that GaN research is much more mature than ZnO. One important topic for another group was the effect of manufacturing variability on the final LED product. The group noted that the ability to obtain high quality substrates directly affects improvements in manufacturing quality and yield. This group also noted that there is still significant core technology work to be done with substrates. This group also considered combining subtask 1.1.1 and 1.1.2 though no consensus was reached.

Participants in another group also expressed concern over moving this subtask to a lower priority when there are still reliability problems with substrates in the market place. The group acknowledged that high quality substrates are needed in order to produce long lifetime, high quality devices. One participant asked rhetorically, 'does it make sense to drop substrates when this could be tied to defect densities and reliability improvements?' Others in this group thought that considerable progress was being made by industry in this area, and that other subtasks deserved to be high priority for the DOE's program.

<table>
<tr><th colspan="2">1.1.2 High-efficiency semiconductor materials</th><th>High Priority</th></tr>
<tr><td colspan="3">Short Descriptor: Research includes creating a more efficient green LED for a better color-mixing device and examining the impact of doping on performance.</td></tr>
<tr><th>Metric</th><th>2006</th><th>Program Target (2015)</th></tr>
<tr><td>• IQE</td><td>20% green, 80% red, 40% blue</td><td>90%</td></tr>
</table>

Priority:
All three breakout groups discussed whether to combine subtasks 1.1.1 and 1.1.2 and/or 1.1.2 and 1.1.3. One group considered a proposal to combine subtasks 1.1.2 and 1.1.3. However, following a discussion that clarified that subtask 1.1.2 is focused on higher efficiency technologies and 1.1.3 is focused on more reliable technologies, there was very little support for the proposal to combine these two subtasks.

Title:
All three LED groups proposed broadening the task title. One group wondered if this subtask should encompass substrate effects on high efficiency materials. Ultimately, this group suggested adding language to the subtask title to include novel approaches to improve efficiency (e.g., quantum dots). In addition to new approaches, participants in another group wanted to broaden the task to include all types of novel materials (e.g., nanostructures). This group proposed the new task to read, "High-efficiency semiconductor materials including novel approaches, materials and structures." One participant in yet another group pointed out that subtask 1.1.2 has the same title as 2.1.2, and suggested that one or both of these titles be revised to clarify the distinction between the two activities.

Short Descriptor:
Two groups agreed that the descriptor should be reworded to highlight green as an important area of research, but not exclusively focus on the green LED. One group went further to suggest adding blue LEDs to the subtask descriptor. They also acknowledged the importance of improving the IQE of the three primary colors in order to achieve a highly efficient (as high as 90% IQE) white device. In addition, another group felt that this subtask descriptor should be clarified to include both phosphor-based and color-mixing LEDs.

Metric:
With regard to the metrics of this task, one group felt DOE should not support research on red light. A participant in this group proposed taking red off the metric list because increasing the thermal conductivity rate of the red emitter is the only area for substantial improvement in the

device. Another group discussed a concern raised by the NGLIA question of whether there really is a good way to measure IQE. The group recognized that since EQE can be measured, a researcher can calculate a rough estimate of the IQE. However the group felt that IQE, even if not measured directly, was the appropriate metric for this subtask.

Status:
A participant in one group felt that the IQE estimate for blue in 2006 was too low, and should instead be 60%.

<table>
<tr><th colspan="2">1.1.3 Reliability and defect physics for improved emitter lifetime and efficiency</th><th>High Priority</th></tr>
<tr><td colspan="3">Short Descriptor: Research areas include dopant and defect physics, device characterization and modeling, and investigation of droop (reduced efficiency at high temperature and current density) to increase lifetime while maintaining wavelength stability.</td></tr>
<tr><th>Metric</th><th>2006</th><th>Program Target (2015)</th></tr>
<tr><td>• Lifetime and efficiency at high current density, $\Delta\lambda$/ºC</td><td></td><td>50k hours and 150 lm/W at 150A/cm^2</td></tr>
</table>

Short Descriptor:
One group was interested in discussing this subtask because it had overall concerns about the reliability and quality of emitters, particularly the color shift over time. There were several fixture manufacturers in this group, and experts with background in conventional lighting technologies. These participants honed in on the importance of stability in the color and quality of emitted light over time. The group acknowledged that lifetime is important, but it is particularly important to understand why phosphor-based LEDs shift color over time, a characteristic that will prevent them from entering the general illumination market.[1] According to one participant, if there is a color shift over time, then the viability of this technology in the lighting design community drops significantly.

This group highlighted the importance for DOE to clarify what it treats as a reliability issue in this subtask. Recognizing this task as a Core Technology research area, the group recommended that this subtask should focus more of its work on addressing chip-related issues, such as the defect density level. This group also discussed the importance of containing lumen variation within a certain product line for a given current density. The group recognized that if you specify that an LED will emit 100 lumens at 350 mA, and the minimum performance of an LED provided has only 60 lumens at 350 mA, that product would be unacceptable. Conventional lighting technologies may have at most product that emits 3% or 5% less lumens below specification. The group concluded that research must be conducted that will improve the reliability of light output for LEDs.

[1] The group recognized that in addition to the problem of phosphor color-shift over time being part of task 1.1.3, it would also be included in subtask 1.3.1, which focuses specifically on phosphors and conversion materials.

Another group briefly addressed subtask 1.1.3. The group considered, but did not ultimately recommend, that subtask 1.1.3 be combined with subtask 1.1.2. A stakeholder in this group asked which materials 1.1.3 referred to. The facilitator clarified that 1.1.3 referred to all materials.

Metric:
This group came up with four proposals to add or clarify the metrics:

1. Questions were raised about why junction temperature was not part of the metric, particularly as this subtask focuses on high drive currents, and junction temperature is a critical aspect of the metrics being measured. The group was concerned that different chip manufacturers may use different reference junction temperatures, and so DOE should specify one. There was unanimous support to add junction temperature to the metrics for 1.1.3.
2. Clarify that efficiency in lm/W relates to electrical watts of energy, not optical watts.
3. Specify wavelength associated with the device color – for instance, if it is a blue LED that is being measured, then it is not possible to achieve the target of 150 lm/W. Therefore, the spectrum must be specified.
4. Add a metric that addresses the maintenance of wavelength stability over time. The group discussed having a limit on the color shift over the life of the lamps, measured in MacAdam ellipses. Life for the LED would be defined as when the LED reaches 70% of its initial lumen output, L_{70}. This group discussed the fact that fluorescent lamps are well within two MacAdam ellipses and questioned whether four ellipses may be appropriate for LEDs.

Task 1.2 Inorganic Device Architecture Research and Modeling
Goal: increase external quantum efficiency

1.2.1 Device approaches, structures and systems		**High Priority**
Short Descriptor: *Work in this area is actually to increase extraction efficiency, but will be measured by progress in EQE.*		
Metric	**2006**	**Program Target (2015)**
• EQE	50%	80%

Priority:
Regarding the subtask priority, one group agreed that since EQE and IQE are such critical factors for success, it is important to keep this subtask as a high priority. In the other two groups, some participants found the distinction unclear between this subtask and subtask 1.2.2, “Strategies for improved light extraction and manipulation.” One stakeholder was unclear whether extraction efficiency in Subtask 1.2.1 referred to the chip or the package. In the other group, a proposal was put forward to combine 1.2.1 and 1.2.2. It was postulated that although 1.2.1 is more device oriented and 1.2.2 is more package oriented, because both focus on extracting light, these two subtasks could be combined. This group was split as to whether or not to combine the tasks.

Short Descriptor:
To clarify the distinction between the subtasks, one group recommended the descriptor should indicate that extraction efficiency is important but other methods of improving EQE are also valid.

Metric:
Regarding the metrics, one group was concerned about a disconnect between extraction efficiency and EQE. While this group did note that extraction efficiency is very hard to measure, a large number of participants in this group felt that EQE was not the best metric for a subtask that focuses only on extraction efficiency. Also, the technical expert for another group pointed out that 1.2.1 focuses on research at the chip level and 1.2.2 focuses on research at the package level, and if they were to be combined (as some in the group had suggested), DOE should maintain separate metrics for tracking chip- and package-level performance.

Target:
One participant in a group questioned the source of the 80% program target. The participant asked if the Department was postulating various types of optical crystals or something along these lines. He expressed his concern over whether the 80% was realistic and/or achievable in 2015, and thought it might be more like 70% or 65%, pointing out that the best photonic crystals only improve extraction efficiency from 30% to 40%. This participant's group decided not to spend time debating the appropriate level, but wanted to record its concern that the 80% target was slightly optimistic. Contrasting this, one participant in another group believed that industry was going to reach the program target of 80% sooner then 2015, however, that achievement would come at a high cost.

1.2.2 Strategies for improved light extraction and manipulation		**High Priority**
Short Descriptor: *Research into integrating optics into the chip, transport structures, device configuration, and reflector design*		
Metric	**2006**	**Program Target (2015)**
• Package efficiency	70%	90%

Priority:
As discussed in subtask 1.2.1, "Device approaches, structures, and systems," two groups desired clarification of the distinction between the two subtasks. In addition, approximately half of one group was in favor of combining the two subtasks.

Metric:
One participant in a group made the comment that "package efficiency" should be changed to "extraction efficiency" to be consistent with the Solid-State Lighting Multi-Year Program Plan.

Target:
One group reviewed the milestones and felt that they were reasonable and achievable. However, the group did not necessarily know how to get the package efficiency up to 90%.

Task 1.3 Inorganic Integration Technology Research
Goal: research technology for high performance LED lamps and luminaires

1.3.1 Phosphors and conversion materials		**High Priority**
Short Descriptor: *Research into high-efficiency phosphors suitable for LEDs, lumen maintenance issues, nanophosphor research.*		
Metric	**2006**	**Program Target (2015)**
• Lumens/Optical Watt (phosphor)	200 lm/optical watt (@6000K and 75 CRI)	250 lm/optical watt (@4100K and 80 CRI)

Short Descriptor:
One group recommended striking "nanophosphor," considering the specificity unnecessary.

Metric:
This group also discussed removing CRI from the metrics for this subtask because a CRI over 80 is difficult to reach, and focusing on CRI could penalize other critical research efforts. However, this group concluded that CRI needed to be included in the metric because there was no other lighting metric or measure that could substitute for CRI at this time. Participants in another group questioned if lumens per optical watt is the proper metric for phosphor conversion. Some participants suggested that phosphor conversion efficiency might be a better metric. However other participants agreed that lumens/optical watt, correlated color temperature, and color rendering index encompassed the biggest hurdles in phosphor research. This discussion was complex and the question may merit further investigation by DOE.

One participant in another group was a manufacturer of phosphors, and remarked that quantum yield or quantum efficiency is an important metric in the development of phosphors. This participant indicated that the quantum efficiency, scattering and Stokes losses are all important to track, and he believed that whether the Department had one number encompassing all efficiencies or broke the metric into three components, the focus would be on the appropriate technical solution. This stakeholder proposed that the Department break the metrics for this task into three components, to better track the performance improvements and put the appropriate incentives in place for industry researchers, a suggestion strongly supported by others. This group supported this proposal almost unanimously. A few participants also discussed the importance of avoiding excessive CCT shift among the phosphor-white LED technologies.

Target:
This group also discussed that the theoretical limit for the phosphor described in the 2015 target would be approximately 380 lumens per optical watt. After losses are taken into account, the achievable efficacy of the phosphor drops to approximately 250 lumens per optical watt. This group discussed what constitutes the 'losses' that reduce the theoretical maximum from 380 to 250 lumens per optical watt. Another group discussed and recommended that the 2015 program target of "4100K and 80 CRI" be changed to a slightly warmer temperature with a higher color rendering index, "3000-4000K and 90 CRI."

Task 1.4: Inorganic Growth and Fabrication Processes and Manufacturing Research
Goal: cross-cutting improvements to growth and fabrication processes and manufacturing

1.4.1 Physical, chemical, optical modeling, measurement, and experimentation for substrate and epitaxial processes	**Medium Priority**
1.4.2 Design and development of in-situ diagnostic tools for the substrate and epitaxial process	**Medium Priority**
1.4.3 Research into low-cost, high-efficiency reactor designs and manufacturing methods	**Medium Priority**

Priority:
One group had extensive discussions on subtasks 1.4.1, 1.4.2, and 1.4.3; however, the group did not recommend changing any priority levels. The discussion centered around stakeholder concern with large variations in chip performance, in terms of color and output. This group identified chip uniformity as a key area for improvement. Nonetheless, the group recommended that DOE focus on chip uniformity only when the fabrication process is stable. A participant pointed out that as long as the process is changing, it is best to wait to address uniformity. Once DOE does focus on chip uniformity, this group acknowledged that it will need a clear metric to track and quantify that uniformity. The group considered as possible metrics thickness, wavelength, and/or luminosity across the chip itself.

Another group considered raising the priority of one of these subtasks. There was considerable discussion about the problems associated with variation in LEDs, and how this problem would prevent or result in slow adoption of this technology by lighting designers and fixture manufacturers. The group thought these three tasks could all be interpreted as addressing some aspect of improving repeatability and reproducibility to reduce variability. Ultimately approximately half the group recommended raising subtask 1.4.1's priority level, also suggesting that the title and/or descriptor drafted should reflect a focus on research that reduces variability in LED chip production.

6.3 LED Product Development Subtask Discussion

Task 2.1 Inorganic Materials and Device Architecture
Goal: increase internal and external quantum efficiency

<table>
<tr><td colspan="2">2.1.2 High-efficiency semiconductor materials</td><td>High Priority</td></tr>
<tr><td colspan="3">Short Descriptor: Develop efficient broadband light emitting materials (including yellow-green, orange, and UV (360nm to 410nm)) and develop alternate low-cost materials (e.g., nitride materials).</td></tr>
<tr><th>Metric</th><th>2006</th><th>Program Target (2015)</th></tr>
<tr><td>• IQE</td><td>20% green, 80% red, 40% blue</td><td>90%</td></tr>
</table>

Priority:
All three LED groups questioned the similarity of this subtask with subtask 1.1.2, "High efficiency semiconductor materials" and recommended that the distinction be emphasized and made clear. One group recognized the value of DOE's program having the ability to conduct core technology research as well as product development on this topic. However, another group suggested possibly dropping this subtask if a clarification cannot be made.

Short Descriptor:
One participant in the group suggested changing "410nm" to "400nm" in order to more accurately represent the wavelength range of UV light. One stakeholder in another group questioned "nitride materials" and thought their mention might be a mistake.

Status:
In addition to calling for addition clarification of the subtask itself, one group questioned the math behind the IQE calculation for blue. The group thought that there seemed to be a problem with the values presented in the milestone table.

Task 2.2 LED Component Technical Integration
Goal: develop cost-effective LED lamps and luminaries

2.2.1 Manufactured materials		**High Priority**
Short Descriptor: *Include phosphors and luminescent materials and high temperature encapsulants and mounting materials.*		
Metric	**2006**	**Program Target (2015)**
• % of original transmission per mm	85-90% (@150°C and 10-15 kHrs)	95% (@150°C Junction Temp. and 50 kHrs)

Metric:
Two groups thought that the metrics in this task needed clarification. One group suggested deleting "per mm." One participant in this group made the comment that if there is higher absorption, the metric should refer to alphas, rather than the % of original transmission. Another group questioned whether transmission should be independent of the wavelength of the light emitted as indicated the program status and target. They discussed this, and proposed two options:

1. One could specify a performance for a particular wavelength or range of wavelengths or,
2. One could take the lowest performing color range and set the program target to that.

Most seemed to think it would be better to specify a wavelength or range of wavelengths with the % of original transmission values.

Target:
Drawing upon their discussion of the metrics, one participant in this group felt that the program targets seem appropriate for red light, but the 2015 target would not be achievable for blue LEDs. Also, this group remarked that it is unclear whether this target assumes an AR coating or

not. For example, if the AR coating is not assumed, then one stakeholder felt that 92% was the highest you could hope to attain as your program target. Another group suggested that the program target junction temperature should be above 185°C, rather than at 150°C.

2.2.3 Electronics Development		**High Priority**
Short Descriptor: *Research in this area includes developing lower cost electronics of smaller size with better color control and longer lifetime.*		
Metric	**2006**	**Program Target (2015)**
• %Energy Conversion	85%	90+%
• $/Watt	0.50 $/Watt	0.10 $/Watt
• X-step MacAdam Ellipse	7-step MacAdam Ellipse	4-step MacAdam Ellipse
• Lifetime	20-50kHrs	50kHrs

<u>Short Descriptor:</u>

One group had an extensive discussion on this subtask, starting with the issue of the device drivers. Many in the group believed that the device drivers are the weakest link in the LED luminaire system, remarking that drivers can operate an LED inefficiently and therefore research here is critical. They suggested that device driver be explicitly mentioned in the subtask descriptor. However, a few participants in this group felt that driver improvements should be funded after LED improvements. This group also felt that this task may also benefit by explicitly mentioning the development of electronics and drivers for automotive applications.

Participants in another group discussed the fact that driving electronics are improving on their own and that the electronics are the key to the success of LEDs. A few participants in this group pointed out that drivers fail before the LEDs, limiting the fixture life. Stakeholders also pointed out areas for development in driver electronics. One area is for the driver to sense the output in RGB devices and to compensate for changes in color. Another stakeholder identified maintaining lumen output for LEDs as a challenge because LEDs reduce their light output as they age and consumers would most likely continue to use them, rather than replace them. To address that, one participant in the group suggested that the driver should switch off the LED when it reaches the end of its lifetime – for example, 70% of original output. This group concluded that the existing drivers in the market today do not meet the needs of lighting designers for general illumination applications.

<u>Metrics</u>

The Red group thought the temperature, color control, and power conversion should be incorporated as metrics. Of these, they specifically felt the power factor was especially important to include. Another group felt that because one of the goals of this subtask is to promote smaller size drivers, a metric tracking volumetric efficiency of the device – such as Watts per cubic centimeter – may be needed.

Status:
One group generally supported the 2006 program status values for this subtask.

Target:
The Red LED group agreed to require a minimum of 0.9 power factor for their added metric and also suggested that the lifetime program target be made to read "greater than 50kHrs." In addition they supported the other program targets because high efficiency, low cost and lifetime were all being tracked. Another group also recommended raising the lifetime program target to be greater than 50kHr, remarking that a lighting designer would want the driver lifetime to be greater than the lamp, so a driver failure would not cause a premature failure of the lamp.

During the report-back plenary session, one topic raised was the issue of the cost per watt of the driver. A participant in one group had suggested the $0.10 per Watt program target was too low, as fluorescent ballasts had already achieved that price point. However, a stakeholder from another group who manufacturers fluorescent ballasts and LED drivers clarified that it depends on the functionality of the driver. This participant indicated that if the driver simply outputs controlled current then $0.10 per Watt may be low, however if the driver controls color, maintains lumen output, and monitors light output functions of the LED, then $0.10 per Watt is an aggressive target.

Task 2.3 System Technology Integration and Novel Luminaire Design

2.3.1 Optical coupling and modeling		**High Priority**
Short Descriptor: *Solving problem of extracting LED photons and getting them to desktop. This includes issues such as coupling to multiple sources and the multi-shadowing problem.*		
Metric	**2006**	**Program Target (2015)**
• Optical/ Fixture Efficiency	70%	90%

Short Descriptor:
One participant in a group raised a question as to whether this task might already be in the mature stage, and perhaps language should be added to the descriptor concerning support for novel applications. Two groups agreed that the short descriptor should read, "Solving problem of extracting LED photons and getting them to task." This revision would not change the fact that issues such as coupling to multiple sources, conversion materials, and the multi-shadowing problem are all included. Rather, the revision would allow researchers to propose projects that address other issues relating to optical coupling and modeling, beyond those explicitly mentioned. One group also preferred that DOE use the term "task" because it is broader than "desktop."

Metric:
One group discussed the importance of adding a metric of cost and lifetime to this subtask. Stakeholders from another group saw the need for metrics for multiple sources and multi-shadowing. One stakeholder suggested the addition of the display metric of just noticeable

difference (JND). This group discussed the fact that the fixture efficiency is not independent of consumer choice. A fixture manufacturer in this group discussed the fact that consumers may choose from a range of finishes on their products, each of which would impact the efficiency of the fixture. This participant indicated that you cannot define the fixture efficiency without defining material and the number of bounces the photons are going to experience before they leave the fixture. This group concluded that fixture efficiency is the right metric, but it's not specific enough. The metric needs to address the beam-spread, as well as other details about the fixture in order to provide an efficiency value that can be measured against and tracked.

Status:
Another group was split on the issue of the 2006 status – some participants believing the 2006 levels of fixture efficiency are around 85 to 90% – and others closer to 60 to 70%.

Target:
One group noted that optical efficiency depends on the application, but agreed that the target of 90% for optical/fixture efficiency is achievable.

2.3.4 Thermal Design		**High Priority**
Short Descriptor: *Solving problem of removing heat away from the emitter chip and reducing thermal resistance to keep LED device at a low operating temperature while integrating the packaged LED device into a luminaire.*		
Metric	**2006**	**Program Target (2015)**
• Thermal resistance (Junction to case)	8-9ºC per Watt	5ºC per Watt

Priority:
Two groups thought this subtask to be redundant with subtask 2.2.2, "LED packages and packaging materials." One of the groups suggested combining the two subtasks. However, this group felt that overall heat removal from the chip to ambient was a more appropriate focus and thus these subtasks should remain separated.

Metric:
These two groups also concluded to change the metric to "junction to ambient." In addition, another two groups discussed whether this metric should be split into two: one at the device level and one for the package system level. Ultimately, one of these groups concluded that this action was appropriate. The other group mentioned that the metric lacks specificity, in that it does not denote the size of the chip nor the number of chips, and that this should be added.

Target:
One group felt that the 5°C per watt is a low program target for 2015. This group felt that the Department should be more aggressive, and should move the target to 3°C for a single chip. At the system level, the group discussed the junction to case temperature of the fixture, and felt that the target of 5°C would be an appropriate junction to luminaire target.

2.3.6 Evaluate luminaire lifetime and performance characteristics		High Priority
Short Descriptor: *Develop reliable information on lamp performance characteristics (e.g., lamp life, UV emission).*		
Metric	**2006**	**Program Target (2015)**
• MTTF (Mean time to failure)		

Title:
One group discussed the title of this subtask, and suggested that this subtask is not "evaluating luminaries" at all, but rather evaluating the LEDs used in those luminaires. It was suggested that the title be modified to clarify this point – it is the evaluation of the LEDs in the luminaire. Furthermore, one participant in this group proposed that this task focus on the Department's study of the technical information on how to manage an LED appropriately so it provides the desired lifetime and performance requirements – for example, the junction temperature in all installations is not 25°C, so a more appropriate temperature would need to be evaluated.

Short Descriptor:
Another group discussed the problem associated with maintained lumen output for LEDs, remarking that as light output decreases with age, consumers would most likely continue to use the LEDs, rather than replace them. To address that, one participant in this group suggested that the driver should switch off the LED when it reaches the end of its lifetime – for example, 70% of original output.

A fixture manufacturer in a group commented that the burden of developing consistent reporting on the performance of LEDs to include in fixtures should fall on LED manufacturers rather than fixture manufacturers. This participant found looking across technical specification sheets that manufacturers don't all report the same data, and when they do, the data is not always reported at the same testing conditions. This variance both in reported specification and performance makes designing and using LEDs in fixtures very difficult. This participant indicated that he would like to see some standardization in this reporting, whether it falls under this subtask or not. This comment prompted a response by an LED manufacturer in the same group who indicated that DOE, ANSI, NEMA and IESNA are all working together at this time to develop exactly what the fixture manufacturer was requesting. This stakeholder also cited a testing program being conducted by the Lighting Research Center, which tests LEDs at different junction temperatures and attempts to forecast life out to fifty thousand hours. This stakeholder indicated that there is a lot of standardization going on at the moment, driven by industry and it would not be necessary to add this to the Department's priority list.

Metric:
This group also discussed the metrics briefly. It was agreed that the mean time to failure (MTTF) was the appropriate metric, in part because it is used to calculate the maintenance cost of lighting installations.

Other Issue Discussed: Programmatic Review

One of the LED break-out groups recommended that DOE hold an annual or biennial physics review of program progress. This group felt that this type of review would ensure DOE remained focused on appropriate and critical research issues that would impact the efficiency and quality of solid-state devices. [Although not discussed in this particular breakout group, DOE has held and continues to hold periodic peer reviews of all its R&D programs, including SSL. These peer review panels are made up of outside independent experts with a range of experience, spanning core technology and product development. The peer review process conducts an assessment of the quality, productivity, and accomplishments of the R&D program, and determines the relevance of program success relative to strategic and programmatic goals and objectives. DOE also uses the peer review process to judge both the merit of individual projects as well as the technical soundness of the overall portfolio. In response to peer review results, the R&D technology development managers formulate Peer Review Implementation Plans that factor into planning, budget and execution decisions made by DOE.]

6.4 Organic Core Technology Subtask Discussion

Task 3.1 OLED Materials Research
Goal: increase internal quantum efficiency through enabling physics and chemistry

<table>
<tr><td colspan="2">3.1.2, 3.2.2 High-efficiency, low-voltage, stable materials and approaches to OLED structures between the electrodes for improved-performance low-cost white-light devices</td><td>High Priority</td></tr>
<tr><td colspan="3">Short Descriptor: This subtask involves material research encompassing stable hole and electron blocking layers and single and multi-layered devices to increase IQE. It also involves engineering between the electrodes (as opposed to chemistry), including layering the device for optimal efficiency.</td></tr>
<tr><th>Metric</th><th>2006</th><th>Program Target (2015)</th></tr>
<tr><td>• IQE</td><td>Singlet: B>20%, W>20%, G>20%
Triplet: G 100%, R 60%</td><td>Singlet: 25%
Triplet: 100%</td></tr>
<tr><td>• Voltage</td><td>4-5 V</td><td>2.8 V</td></tr>
<tr><td>• T70 at 1000 cd/m2</td><td></td><td>T70 = 40,000 hours</td></tr>
</table>

Priority:
Both groups showed no opposition to keeping subtask 3.1.2, 3.2.2 as high priority items for OLED research. One group remarked that before OLEDs can be commercialized, higher efficiencies must be achieved. The other group collectively agreed that combining subtasks 3.1.2 and 3.2.2 was an appropriate change because modifications in OLED structure and OLED materials were intimately connected. However, one participant of that group voiced concern over the broadness of the subtask, commenting that it may limit resources for the large number of projects covered.

Title:
Both groups suggested eliminating the words "between the electrodes." The technical expert of one group explained that "between the electrodes" was added to distinguish subtask 3.1.2 and 3.2.1, "Strategies for improved light extraction and manipulation." A participant suggested that one could eliminate the words "between the electrodes" and add the word "organic" to describe the materials used. However, another stakeholder noted that by adding the word "organic" one would eliminate the development and use of important materials like LiF. In response, another participant stated that it is hard to separate the electrode from the device. The interface of the electrode and the organic material is important for charge injection and ultimately device performance. It was also noted that by removing the words "between the electrodes" one recognizes the importance of researching better cathode technologies and more stable anode technologies.

In the other OLED group there was consensus that the wording of the subtask title was awkward and repetitive. One participant commented that in fact the subtask should be expanded to include the substrate because there are issues with the porosity of substrates. Additions of barrier coatings require refractive index matching and affect overall OLED structure and materials. However, others responded that there were few Core Technology inventions to be made in substrates and that substrate research may more appropriately fall under Product Development. While one group only deleted "between the electrodes" the other group's final suggested title for subtask 3.1.2, 3.2.2 was "Materials and approaches toward high-efficiency, low voltage stable devices for improved-performance low-cost white-light."

Metric:
One OLED group had extensive discussion on the appropriateness of using voltage as a metric. A participant commented that lm/W is a more important metric as it is a direct measurement of overall efficacy. Another participant supported that comment, remarking that to specify voltage as a metric may restrict solutions increasing efficacy to only low voltage solutions. Other participants advocated voltage as a metric, saying that lowering voltage is necessary to increase OLED efficacy. In addition, voltage was said to be a more appropriate measurement parameter for Core Technology research and very important as it affects device lifetime and degradation. Ultimately most of the group was in favor of including lm/W as a metric for the subtask. A few group members commented that the inclusion of both voltage and lm/W was redundant. In addition, it was discussed in both groups that all metrics should be specified at brightness of 1000 cd/m^2. One participant also suggested that color should be specified for each metric.

Status:
One OLED group suggested adding to the 2006 status, 100% IQE for a blue triplet emitter as this has already been achieved.

Target:
One group was at near consensus suggesting that the 2015 Program Target voltage should be raised. They mentioned that 2.8 V closely corresponded to the energy of a blue photon and therefore the target was too ambitious. However, the other OLED group decided that the 2015 Program Targets were appropriate. One participant in that group also wondered whether 2.8 V

may be too ambitious, but another participant commented that many polymer devices have already achieved this program target.

Task 3.2 OLED Device Architecture Research and Modeling
Goal: increase external quantum efficiency

3.2.1 Strategies for improved light extraction and manipulation		**High Priority**
Short Descriptor: *This subtask involves research into optical and device design for improving light extraction.*		
Metric	**2006**	**Program Target (2015)**
• Extraction Efficiency	20%-30%	80%

Short Descriptor:
Regarding the short descriptor, one group reached near consensus that the descriptor should be expanded to include research in material design to improve light extraction. A participant provided the example that one way to affect light extraction is to modify the refractive index which is a materials issue. The participant suggested replacing the word "device" with "device/material."

Status:
One group decided that 20%-30% extraction efficiency was too low and that 30%-40% extraction efficiency should be the new status.

Target:
A participant noted that 80% was high for a program target if one wanted to achieve a highly efficient, stable device. However, it was agreed in that group that this program target could be reached for a device if the device did not need to be either efficient or stable.

3.2.3 Research on low-cost transparent electrodes		**High Priority**
Short Descriptor: *This subtask involves research into better transparent electrode technology that offers an improvement over ITO cost and deposition rate and allows for roll-to-roll manufacturing.*		
Metric	**2006**	**Program Target (2015)**
• Ohms/□	Flexible: 40 Ohms/□	Flexible: <10 Ohms/□
• Transparency	75%-80%	92%
• $/m^2		<$1/m^2

Short Descriptor:
Discussion arose in the Green OLED group regarding the relevance to Core Research of the words "ITO cost" in the short descriptor. One participant felt that ITO cost was a manufacturing problem and therefore belongs as a Product Development subtask. However, the Green OLED

group eventually reached consensus that there are in fact two types of cost associated with electrodes: materials cost and manufacturing cost. They agreed that manufacturing cost factors, such as deposition rate and high capacity techniques, belonged under a Product Development subtask. Approximately 90% of the group believed that materials cost could be classified under Core Technology since it involved the search for new electrode alternatives. The Green OLED group ultimately decided to delete “and deposition rate and allows for roll-to-roll manufacturing” from the short descriptor and agreed to relocate it in Product Development subtasks 4.1.1 and 4.4.1.

The Blue OLED group felt that developing a flexible electrode would eventually help lower the cost of OLEDs by allowing for roll-to-roll manufacturing. However, participants believed that one could achieve low cost OLEDs using other manufacturing techniques that did not require flexible electrodes. Therefore it was suggested to replace “allows for roll-to-roll manufacturing” with the words “and allows for low-cost OLED manufacturing such as roll-to-roll manufacturing.” Participants also agreed that if one did not delete the words “in between the electrodes” from subtask 3.1.2, 3.2.2, one should modify the language to include the research of not only cost-effective but also “stable” electrodes.

<u>Metric:</u>
Drawing upon their discussion regarding the short descriptor, the Green OLED group questioned the relevance of “$\$/m^2$” as a useful metric for a Core Technology subtask. There was strong consensus that it was a difficult metric to measure, especially when dealing with new materials. The group suggested changing “$\$/m^2$” to “materials cost” in order to more appropriately characterize the cost of the new electrode. The Blue OLED group felt that the cost of the electrode was the most important driver in this subtask. In addition a participant suggested adding “absorption” or “internal transmittance” as a metric because “n” and “k” were eliminated by the NGLIA. The group agreed that adding “in the visible wavelengths” to qualify the transparency of the electrode would sufficiently characterize the electrode.

<u>Status:</u>
The Blue OLED group tried to develop a 2006 status for the cost of ITO but realized that only the price of ITO ($\$86/m^2$) was known and not the manufacturing cost. Because the Blue OLED group changed the short descriptor, they decided it was necessary to add values associated with rigid electrodes to the existing 2006 status and program targets. The resistance (10 ohms/□) and transparency (90%) of ITO was agreed to be the best transparent electrode available today.

<u>Target:</u>
Drawing upon their discussion of the metrics, the Blue group agreed that <5 ohms/□ and the transparency of glass (92%) should be rigid electrodes program targets. Discussion arose in the Green OLED group regarding the 2015 Program Target of “$<\$1/m^2$.” One participant in the Green group argued that the $\$1/m^2$ seemed very unrealistic. He suggested that perhaps this target was based upon where the technology should be in order to be competitive with existing technologies. The group questioned the validity of this approach to determine program targets. In addition, they strongly supported setting the 2015 Program Target for the added metric “materials cost” to “less than ITO.” Participants felt that it would be unwise to set a particular price since it would be difficult to predict the price of ITO in 2015.

Task 3.3 OLED Technology Integration
Goal: research technology for high performance OLED lamps and luminaires

3.3.2 Low-cost encapsulation and packaging technology	**Medium Priority**
Short Descriptor: *This subtask involves working on low-cost ways to seal the device to protect the luminaire from its environment to ensure a long device lifetime.*	

Priority:
One group discussed this subtask and decided that it is appropriate as a medium priority. It was noted that not only is this subtask being funded as a high priority research subtask at the product level but it was also noted that packaging is very important for displays. Once companies interested in manufacturing displays develop high quality encapsulation and packaging technologies, the technology will be easily transferred to OLEDs intended for general illumination applications.

Task 3.4 Organic Growth and Fabrication Processes and Manufacturing Issues
Goal: develop equipment and tools for low-cost, high-yield manufacturing

3.4.2 Investigation of low-cost fabrication and patterning techniques and tools		**High Priority**
Short Descriptor: *This subtask includes modeling to understand the fabrication process and fundamentally improved fabrication processes.*		
Metric	**2006**	**Program Target (2015)**
• Deposition Speed • Material Utilization		

Metric:
Regarding the metrics of subtask 3.4.2, one group engaged in discussion on the utility, relevance, and practicality of using deposition speed and material utilization as metrics. Some participants believed that trying to quantify the two metrics would be difficult within a Core Technology subtask and no further definition was necessary. Other participants argued that deposition speed and material utilization are important and accurately measure the necessity for new technologies and more efficient production of OLEDs. Within that group there was approximately a 50/50 split regarding the use of the two metrics. The other OLED group also debated the utility of the metrics. One participant argued that deposition speed was a metric that was more appropriate in product development. However, the majority of the group disagreed. The group also felt it was necessary to clarify the term deposition speed. Some participants felt that the speed of depositing a certain thickness "nm/s" was important while others felt that the speed of depositing an entire device was more important "m^2/s". The group decided both metrics were useful and that "nm/s with a tool that is scalable to m^2 substrates" was a reasonable way to measure the speed of a manufacturing technique.

Status:
To determine the 2006 status of deposition speed and material utilization a participant suggested obtaining current production speeds and material usage data from an existing OLED company.

Target:
To determine the 2015 deposition speed program target, a participant from one group suggested back-calculating it from other projections developed in past DOE literature. The other OLED group collectively suggested that "10-30 nm/s with a tool scalable to m^2 substrates" would be an ambitious but reachable program target for deposition speed. One participant wondered if 98% was a good program target for material utilization while another suggested 90% was sufficient as much of the material would coat the walls of the chamber. No consensus was reached.

6.5 Organic Product Development Subtask Discussion

Task 4.1 OLED Materials Development
Goal: develop devices with increased internal quantum efficiency

4.1.1 Low-cost substrates		**High Priority**
Short Descriptor: *This subtask includes developing low cost, readily available substrates with a low water permeability and high thermal conductivity*		
Metric	**2006**	**Program Target (2015)**
• Cost		<$3/m2
• Thermal • Conductivity		10x
• % Dark Spot Area		<10% dark spots at T70

Title:
There was considerable discussion in both groups regarding whether "substrates" referred to just the substrate or both the substrate and electrode. Green OLED group participants suggested changing "substrates" to "substrates and transparent electrodes," arguing that anyone who designs a substrate will have to examine the electrode as well. Participants in the Blue OLED group suggested changing the title to "Low-cost substrates integrated with transparent conductive electrodes," arguing that the electrode and substrate comprise a system both with equal weight. Adding this term also helps differentiate between this subtask and subtask 4.3.1, entitled "OLED encapsulation packaging for lighting applications." However, members of the Green OLED group commented that by grouping the substrate and electrode together, you might be restricting research to transparent electrodes tethered to the substrate. They mentioned that there is significant research in OLEDs with transparent electrodes deposited on top of the device structures. The Green OLED group decided to reserve opportunities for transparent electrode research for subtasks 3.2.3 and 4.4.1.

Short Descriptor:
Regarding the short descriptor of subtask 4.1.1, the Green OLED group thought that this would be an appropriate place to relocate part of the eliminated phrase of subtask 3.2.3's short descriptor. In subtask 3.2.3, the Green OLED group had suggested the omission of the concept of high deposition rate and roll-to-roll manufacturing of transparent electrodes and advised its transfer to a Product Development subtask. In their previous discussion they had also noted the intimate connection between substrate and electrode, especially in the case where one is investigating resistivity of flexible electrodes, as subtask 3.2.3's metrics indicate. Because of this relationship, multiple participants suggested the inclusion of the development of substrates for mass production in subtask 4.1.1's short descriptor. Also, there was large agreement that "roll-to-roll manufacturing" should be replaced with a more general term such as "high-capacity manufacturing" to allow for other low cost substrate manufacturing options. There was near consensus to the Green OLED group's suggestion to add "This includes developing substrates for high-capacity, low-cost manufacturing" to the end of the subtask's short descriptor.

Metric:
Discussion arose in both groups over the usage and importance of thermal conductivity as a metric for OLEDs. Some participants questioned whether there was considerable room for improvement in thermal conductivity since most substrates use glass. However, another participant argued that technologies such as nanotubes can conduct heat away from the device and therefore thermal conductivity is an area in which innovative research can make significant change. Regarding the importance of thermal conductivity, multiple participants commented that at low wattages (at which OLEDs are expected to perform) thermal conductivity is less important because less heat is generated. In response, one participant argued that thermal conductivity is critical not only during performance but also while processing the device. The majority of one OLED group was in favor of keep thermal conductivity as a metric while the other OLED group suggested removing it.

Regarding % dark area as a metric, the both groups required further clarification on the definition and operating conditions. Several participants in one group remarked that dark spots increase in a device regardless of whether it is or is not operating. Therefore, one should use % dark spot area at 5 years shelf life instead of % dark spot area when a device reaches 70% lumen maintenance. Another participant thought one should use the permeability of the substrate (g/m^2/unit time) as a metric. However, another participant explained that one measures permeability of a substrate by counting dark spots. The group agreed that % dark spot area at 5 years shelf life is the most appropriate metric.

Status:
Regarding the cost program status, one participant noted that a study on the feasibility of organic solar cells stated that the cost of glass today is \$0.46/ft^2, which is about \$5/m^2.

Target:
Discussion arose in both groups about the 2015 Program Target substrate cost of <\$3/m^2. Participants commented that the substrate cost depends entirely on the type of material being used. Members in one group thought a program target of \$3/m^2 is reasonable for glass but may be too ambitious for a flexible substrate. A participant remarked that flexible plastic (thin-pc) is

currently cheaper than glass though the group decided it is too permeable to be considered a viable substrate. Another participant wondered if \$10/m^2 would be a better target. However, no consensus was reached. In the other group, a participant mentioned that currently, unconverted glass costs approximately \$3/m^2, after which it needs to be prepared adding cost to the substrate. In general, that group questioned the feasibility of the target goal and required further clarification on the exact definition of cost.

<table>
<tr><td colspan="2">4.1.2, 4.2.2 Between electrodes high-efficiency, low-voltage materials and architectures that improve device robustness, increase lifetime and increase efficiency</td><td>High Priority</td></tr>
<tr><td colspan="3">Short Descriptor: This subtask involves developing architectures and materials that improve robustness, lifetime, and efficienc, and the optimization of materials that show mass production potential.</td></tr>
<tr><th>Metric</th><th>2006</th><th>Program Target (2015)</th></tr>
<tr><td>• Efficacy (lm/W)</td><td>32 lm/W</td><td>>100 lm/W</td></tr>
<tr><td>• CRI</td><td></td><td>90</td></tr>
<tr><td>• EQE</td><td></td><td></td></tr>
<tr><td>• Voltage</td><td></td><td>2.8 V</td></tr>
<tr><td>• T70 at 1000 cd/m^2</td><td></td><td>T70 = 40,000 hrs</td></tr>
</table>

Priority:
Though both groups agreed that this subtask is an appropriate high priority for OLED research, both groups also tried to clarify the distinction between this subtask and subtask 3.1.2, 3.2.2, “High-efficiency, low-voltage, stable materials and approaches to OLED structures between the electrodes for improved-performance low-cost white-light devices.” To clarify this distinction, one group suggested changing the title while the other suggested changing the short descriptor.

Title:
The Green OLED group collectively recommended directing the subtask toward the development of devices with mass production potential. In addition, the group agreed that the reference to low-voltage materials did not seem sensible as the voltage of a material cannot be measured. There was strong support to change the title of subtask 4.1.2, 4.2.2 to “Scalability of optimized materials and device architectures for low cost manufacturable white OLEDs.” The Blue OLED group, on the other hand, felt that the title was appropriate if one merely eliminated the words “between the electrodes.” Because one cannot develop a device without electrodes, these words confined the subtask more than was appropriate.

Short Descriptor:
Regarding the short descriptor, participants in the Blue OLED group noted that subtask 3.1.2, 3.2.2 focuses more on revolutionary approaches to each component of the OLED device while subtask 4.1.2, 4.2.2 should focus on a system-oriented approach that uses ideas and materials developed in 3.1.2, 3.2.2 to improve the efficiency of the device while taking into account important factors like scalability and stability. A member of NETL (National Energy Technology Laboratory) explained to the group that to get funding in this subtask a researcher

must show a pathway to market. It was agreed that a system-oriented approach was a necessary step to developing a successful pathway to market. To implement this idea, the group suggested adding to the descriptor the words “developing and improving system architectures and materials.” The other OLED group thought the descriptor required further clarification of “robustness.”

Metric:

In discussing the metrics, the Green OLED group thought that the existing metrics were no longer sufficient for their modified subtask title and description. The group felt that an additional metric measuring scalability was necessary. When one participant suggested using OLED device area as a metric, another participant argued that total luminous output (independent of device area) is the important parameter for OLED lighting applications. Also, it was suggested that since scalability is an emphasis in the modified subtask, “manufacturer potential cost” should also be included as a metric of manufacturability and processibility. There was near consensus to use “total lumens” and “manufacturer potential cost” as additional metrics.

Several members of the Blue OLED group also suggested that either total lumens or lumens/m^2 would be a better metric for this subtask. It was noted that though cd/m^2 does signify the brightness of the lamp, the number of lumens emitted from a single device is more important. However, no consensus was reached. A few participants in the Blue OLED group thought that one should use size as a metric to distinguish between devices in this subtask versus those in 3.1.2, 3.2.2. However, the majority of the group thought that it was unreasonable to request all researchers in this area to produce large scale devices. Another participant in the Blue group noted that metrics such as EQE and voltage are meaningless, as lm/W characterizes all aspects of device efficiency. The group agreed that these values are relatively more important in Core Technology and should be eliminated from this subtask. Participants also remarked that CRI is meaningless unless further specified. The group agreed to add “at CCT on a blackbody locus” to describe the CRI.

Target:

One participant suggested defining the 2015 goal as white OLED as a fluorescent replacement. The Green OLED group defined a white OLED of 100 lm/W, 90 CRI, 40,000 hours L_{70}, and 3000 lumens output as the representative target unit. A participant from the other OLED group suggested that 1,000 lumens was the absolute minimum amount an OLED device could emit to be competitive in the general illumination market. In addition, for the Green group’s added “manufacturer potential cost” metric, it was suggested and accepted by the Green OLED group to use $10/klm as the 2015 Program Target. This number was obtained from Table 4-3 in the Solid-State Lighting Multi-Year Program Plan.

Task 4.2. OLED Device Architecture Development
Goal: develop devices with increased external quantum efficiency

4.2.1 Implementing strategies for improved light extraction and manipulation		**High Priority**
Short Descriptor: *This subtask involves improving on known approaches for extracting light.*		
Metric	**2006**	**Program Target (2015)**
• Extraction Efficiency	25%-30%	90%

<u>Target:</u>
Both groups questioned the discrepancy in the 2015 Program Target when compared to the target of subtask 3.2.1. One very strongly recommended changing the 2015 Program Target to 80% for consistency with subtask 3.2.1. The other group agreed that the Program Target should be lower in the product development subtask than in the core task, because certain compromises must be made in a commercial product. This group decided that 70% extraction efficiency is a sufficient target.

Task 4.3. OLED Technology Integration
Goal: develop efficient and reliable OLED lamps and luminaires

4.3.1 OLED encapsulation packaging for lighting applications		**High Priority**
Short Descriptor: *This subtask includes research in heat management, dissipation techniques, encapsulants, and down-conversion materials for maximizing high-quality lumen output and reduced water permeability.*		
Metric	**2006**	**Program Target (2015)**
• $/m^2	$4/m^2	$3/m^2
• % Dark Spot Area		<10% dark spots at T70
• Loss Penalty (compared to glass)		0%

<u>Metric:</u>
Regarding the metrics, one group agreed that they were appropriate for the subtask. However, similar to subtask 4.1.1, "Low cost substrates," the group required further definition and clarification of "% dark spot area." The other group agreed that like subtask 4.1.1, the "% dark spot area" metric should be clarified by adding the words "at a shelf life of 5 years."

<u>Status:</u>
Both OLED groups also questioned the 2006 status value for the cost of encapsulation. One group collectively believed that both of these values were low, but had no suggestions for specific values to replace them. One participant suggested using analysis done for organic photovoltaic encapsulation to determine these values. However, other members of the group argued that OLEDs required more expensive encapsulation due to their high water sensitivity.

The other OLED group agreed that the 2006 metric should be more expensive than the program target because in the future, OLEDs will be printed on thinner sheets of material.

Target:
Participants in both groups remarked that the 2015 Program Target for the cost of encapsulation was too low. A participant in one group suggested \$10/m^2 as a more appropriate program target. However, other participants remarked that aluminum costs less than \$3/m^2 and this subtask does not include the substrate. Ultimately one group decided that \$3/m^2 is an appropriate target while the other believed it still needs to be raised.

Task 4.4. OLED Growth and Fabrication Processes and Manufacturing Issues
Goal: develop equipment and tools for low-cost, high-yield manufacturing

4.4.1 Module and process optimization and manufacturing		**High Priority**
Short Descriptor: *This subtask involves inventing and adapting OLED manufacturing technologies to the needs of lighting. It also covers developing flexible substrates for roll-to-roll manufacturing.*		
Metric	**2006**	**Program Target (2015)**
• Luminaire Cost/m^2		<\$30/m^2

Short Descriptor:
Regarding the short descriptor of subtask 4.4.1, the Green OLED group felt that this would be an appropriate place to relocate part of their eliminated phrase of subtask 3.2.3's short descriptor. In subtask 3.2.3, the Green OLED group had suggested the omission of the concept of high deposition rate and roll-to-roll manufacturing of transparent electrodes and advised its transfer to a Product Development subtask. In addition, the group agreed that because the development of substrates conducive to high capacity manufacturing was now covered in subtask 4.1.1, it should be omitted from this subtask descriptor. There was strong consensus to change the short descriptor to "This subtask involves inventing and adapting OLED manufacturing technologies to the needs of lighting including low cost fabrication of transparent electrodes."

Metric:
Discussion arose in both groups concerning the inclusion of \$/lm as an additional metric. Similar to the discussion regarding subtask 4.1.2, 4.2.2, multiple participants in one group argued that cost per lumen was an important metric to consider. The group was at near consensus to include \$/lm. One participant in the other group suggested that the metric should instead be based on the lamp cost/m^2 instead of luminaire cost/m^2. Ultimately, however, the Blue group agreed to keep the metric at luminaire cost/m^2 because fixtures may be unnecessary for OLEDs used in general illumination applications.

Status:
One group also discussed the current status of the price of an OLED Luminaire. One member suggested \$200-\$300/m^2 as a reasonable figure. Other members thought the luminaire may cost

even more. However, because there are currently no OLEDs commercialized for general illumination purposes, the group decided not to settle on a number.

Target:

For consistency, one group agreed upon using $10/klm as 2015 program target. In addition multiple participants voiced concern over the feasibility of obtaining a luminaire at less that $\$30/m^2$ and were unsure if this value was a reasonable target.

7. Next Steps

Moving forward, the Department of Energy will continue to work closely with the Alliance, SSL industry, R&D community, energy efficiency organizations, utilities, and standards generating organizations to speed energy-efficient SSL technologies from lab to market.

In February 2007, DOE announced the selection of five laboratories as a pre-qualification to conduct tests of market-available SSL products in support of the DOE SSL Commercial Product Testing Program. In March, DOE announced the selection of two energy efficiency organizations to work with DOE to establish the DOE SSL Technical Information Network. In March 2007, DOE issued an "Invitation to Participate" to SSL manufacturers for products to be placed in buildings for DOE demonstration projects in Summer 2007.

Selections for Core Technology Research (Round 3) and Product Development (Round 3) solicitations are expected in Spring 2007. DOE anticipates issuing competitive solicitations for Core Technology Research (Round 4) and Product Development (Round 4) in Spring/Summer 2007. In September, DOE's Small Business Innovation Research (SBIR) Program (http://sbir.er.doe.gov/sbir/) will issue its annual solicitation, and in October, DOE's Basic Energy Sciences Program (http://www.sc.doe.gov/grants/FAPN06-01.html) will issue its annual solicitation. Both solicitations include topics related to solid-state lighting. To register for ongoing updates related to DOE SSL solicitations, see: http://www.netl.doe.gov/ssl.

7.1 Voices for SSL Efficiency: Opportunities to Partner and Participation

In April, DOE and Southern California Edison will host a workshop in Pasadena, California, focused on identifying opportunities for Federal, State, and private-sector organizations to work together to shape markets for high-performance, high efficiency SSL products. Workshop highlights include:

- Emerging SSL markets for general illumination – timing and niches
- Case studies on early SSL applications
- DOE's five-year commercialization support plan, including ENERGY STAR, testing, standards, demonstrations, competitions, and opportunities to participate
- SSL product rollout scenarios – priorities and potential roles for government, industry, efficiency organizations, utilities, and others
- SSL essentials: technology, applications, advantages, disadvantages

To learn more, see: http://www.netl.doe.gov/ssl/PasadenaWorkshop.html.

8. Appendices

Appendix A: SSL R&D Workshop Registrants List
Appendix B: DOE SSL Program Fact Sheets

- Guiding Technology Advances from laboratory to Marketplace
- Coordinated Efforts Provide Enabling Knowledge to Advance SSL Technology
- Operational Plan for SSL R&D
- Solid-State Lighting Patents Submitted as a Result of DOE-Funded Projects
- Guiding Market Introduction of High Efficiency, High-Performance SSL Products

Appendix C: Background Material for R&D Priorities Breakout Session – DOE SSL R&D Tasks and Subtasks
Appendix D: DOE Solid-State Lighting Program Commercialization Support Pathway

APPENDIX A: SSL R&D Workshop Registrants List

Registrant's Name	Company
Srinath Aanegola	GELcore
Curtis Abbott	Lucesco Lighting Inc.
Gregg Ander	Southern California Edison
Tony Andrady	RTI International
Mehmet Arik	GE Global Research Center
Keith Bahde	Gallium Lighting, LLC
Karen Baker	OptoLum, Inc.
Daniel Barton	Sandia National Laboratories
Bill Beakes	Armstrong World Industries
Jeffrey Beiter	Sea Gull Lighting Products, LLC
Rolf Bergman	Rolf Bergman Consulting
Joseph Berry	National Renewable Energy Laboratory
Dietrich Bertram	Philips Lighting
Thomas Betty	Nebula Lighting Systems
Vrinda Bhandarkar	Strategies Unlimited
Robert Biefeld	Sandia National Laboratories
Mary Boone	Plextronics
Laura Brennecka	Cabot Corporation
Richard Brenner	PolyBrite International
James Brodrick	U. S. Department of Energy
Doug Brookman	Public Solutions, Inc.
Robert J. Burdalski, Sr.	Lamina
Diana Burk	Navigant Consulting, Inc.
Geoffrey Burnham	Agiltron, Inc.
Mark Burnham	Heatron
Anthony Burrell	Los Alamos National Laboratory
Paul Burrows	Battelle, Pacific Northwest National Lab
Densen Cao	CAO Group, Inc.
Xian-An Cao	West Virginia University
Joel Chaddock	National Energy Technology Laboratory
Jian Chen	Nanosys, Inc.
DJ Chou	enLux Lighting
Eddie Christy	National Energy Technology Laboratory
Michael Coltrin	Sandia National Laboratories
Edward Crofton	Articulated Technologies, LLC
Brian Crone	Los Alamos National Laboratory
John Curran	Dialight Corporation
Brian D'Andrade	Universal Display Corporation
Edward Daniels	Argonne National Laboratory
Ronald Daubach	OSRAM SYLVANIA
Dr. Tom Davenport	Optical Research Associates
Lynn Davis	RTI International
Robert Davis	Carnegie Mellon University
Gordon Day	Optoelectronics Industry Development Association
Robert P. Devaty	University of Pittsburgh
Brian Dlugosch	AIXTRON Inc.

Montu Doshi	University of Colorado, Boulder
Brian Dotson	National Energy Technology Laboratory
Kevin Dowling	Color Kinetics/NGLIA
Anil Duggal	GE Global Research Center
Russell Dupuis	Georgia Institute of Technology
Marc Dyble	OSRAM Opto Semiconductors
Ryan Egidi	National Energy Technology Laboratory
Jeffrey Elam	Argonne National Laboratory
David Elien	GELcore
David Ensor	RTI International
Robert Erhardt	Philips - Advance
Waqidi Falicoff	LPI
Todd Fast	Lucere Lighting
Ian Ferguson	Georgia Institute of Technology
Alec Fischer	Arizona State University
Arthur Fischer	Sandia National Laboratories
Timothy Fitzsimmons	U.S. Department of Energy
Robert Forcier	RoseStreet Energy
Michael Fusco	LED Specialists
Jim Gaines	Philips Lighting Electronics
Rafael Garcia	Arizona State University
Lijian Geng	CAO Group, Inc.
David Geohegan	Oak Ridge National Laboratory
Kelly Gordon	Pacific Northwest National Laboratory
Wayne Guillien	Ruud Lighting
Mahima Gupta	Navigant Consulting, Inc.
Caterina Hall	Light Integration Technologies
Monica Hansen	Cree SBTC
Andrew Hanser	Kyma Technologies, Inc.
Rene Helbing	Avago Technologies
Jose Luis Hernandez	CSA
Angela Hohl-AbiChedid	OSRAM SYLVANIA
Dawn Hollingsworth	Visual Terrain
Bin Hu	University of Tennessee
Hanna Huang	American Bright Optoelectronics
Patrick Hughes	Oak Ridge National Laboratory
Roy Hughes	BC Hydro/LDL
Gradimir Ilic	BC Hydro
James Intrater	Materials Modification, Inc.
Bryan Irrgang	Long Island Power Authority
Ilia Ivanov	Oak Ridge National Laboratory
Jack Ivey	Altair Engineering
Fred Jaeger	Affiliated Management, Inc.
Huiping Jia	University of Texas at Dallas
Quanxi Jia	Los Alamos National Laboratory
Feng Jin	Ball State University
Karl Jonietz	Los Alamos National Laboratory
Dr. Keith Kahen	Eastman Kodak

Mary Beth Kaiser	Mary Beth Kaiser Company
Shawn Keeney	Dialight Corporation
George Kelly	Aurora Optical
John Kerr	Lawrence Berkeley National Laboratory
Garo Khanarian	Rohm and Haas
Greg King	Wostec
Bruce Kinzey	Pacific Northwest National Laboratory
Mike Ko	Intematix Corporation
Glenn Kohnke	Corning Incorporated
Daniel Koleske	Sandia National Laboratories
Sandy Kushner	Air Products & Chemicals, Inc.
Susan Larson	Neo-Neon
Michael Lebby	Optoelectronics Industry Development Association
Marc Ledbetter	Pacific Northwest National Laboratory
Lawrence Lee	American Bright Optoelectronics
Wayne Letwink, Jr.	Dialight Corporation
Leslie Levine	
Jing Li	Arizona State University
Andrew Lipman	Next Generation Lighting
Igor Lisitsyn	GE
Gao Liu	Lawrence Berkeley National Laboratory
Heng Liu	BridgeLux, Inc.
Jianlin Liu	UC Riverside
Doug Loy	Flexible Display Center
Vireak Ly	Southern California Edison
Sean Lyne	Unity Microslectronics, Inc.
Samuel Mao	Lawrence Berkeley National Laboratory
Karen Marchese	Akoya
Jim Marquardt	SRP
James Martin	Sandia National Laboratories
Ronald Mascenti	enLux Lighting
Curt Maxey	Oak Ridge National Laboratory
T. Mark McCleskey	Los Alamos National Laboratory
Scott McCreary	CONCUR Inc.
Michael McGehee	Control Technologies
Kelly McGroddy	UCSB
Margaret McInerney	Navigant Consulting, Inc.
John McKinness	Leotek Electronics Corp.
Joanna McKittrick	UC San Diego
Dwight McMillan	Solareve, Pure LED
Jin Mei	Arizona State University
Hisham Menkara	PhosphorTech
Cynthia Merrell	LED Lighting Fixtures, Inc.
Alexander Mikhailovsky	University of California, Santa Barbara
Kailash Mishra	OSRAM SYLVANIA
Martin Moeck	Arizona State University
Brian Moeckly	Superconductor Technologies, Inc.
G R Mortenson	QuNano

Theodore Moustakas	Boston University
Jeff Nause	Cermet, Inc.
Guy Newsham	National Research Council Canada
Liam Noailles	Cabot Corporation
Ann Norris	Dow Corning Corporation
David Norton	University of Florida
Arto Nurmikko	Brown University
John A. Nychka	University of Kentucky
John Nylander	Light Integration Technologies
Yoshi Ohno	NIST
Mohammad Omary	University of North Texas
Mia Paget	Pacific Northwest National Laboratory
Timothy Palucka	Akoya
Steve Paolini	Philips Lumileds Lighting
Alexander Parfenov	Physical Optics Corporation
Noel Park	Nanostellar
Yoon Soo Park	Rensselaer Polytechnic Institute (RPI)
Jitendra Patel	Infinilux
James Patterson	University of Colorado, Boulder
Paul Pattison	National Energy Technology Laboratory
David G. Pelka	InteLED
Edward Petrow	Lincoln Technical Services, Inc.
Gregory Phelan	Advanced Electroluminescent Sciences
Kyle Pitsor	National Electrical Mfrs Assn (NEMA)
Eric Poncelet	CONCUR, Inc.
Jeff Popielarczyk	General Electric
Michael Poplawski	ON Semiconductor
Vinay Prakash	USHIO AMERICA INC.
Chris Primous	Progress Lighting
Jeff Quinlan	Acuity Brands Lighting
Jonathan Raab	Raab Associates, Ltd.
William Reisenauer	LED Specialists
Michael Reznikov	Physical Optics Corporation
Kurt Riesenberg	National Electrical Mfrs Assn (NEMA)
Spilios Riyopoulos	SAIC
Victor Roberts	Roberts Research & Consulting, Inc.
Larry Roderick	k Technology Corporation
Lauren Rohwer	Sandia National Laboratories
Mark Rosenberg	Nebula Lighting Systems
Alan Ruud	Ruud Lighting, Inc.
Bruce Ryan	Maui Product Development
Marci Sanders	NW Energy Efficiency Alliance
Tim Sands	Purdue University
Linda Sapochak	Battelle, Pacific Northwest National Laboratory
William Schaff	RoseStreet Labs Energy
Paul Scheidt	Cree, Inc.
John Schlueter	Argonne National Laboratory
Edward Schmidt	Northeast Energy Efficiency Partnerships

Michael Scholand	Navigant Consulting, Inc.
Anant Setlur	GE Global Research Center
Yijian Shi	SRI International
Joseph Shiang	GE Global Research Center
Paul Shnitser	Physical Optics Corporation
Anatoly Shteynberg	Exclara/Synditec
Gary Silverman	Arkema Inc.
David Simon	Altair Engineering, Inc.
Darryl Smith	Los Alamos National Laboratory
Bob Smith, PE	Cooper Lighting
Oleksiy Snezhko	Argonne National Laboratory
Franky So	University of Florida
Christopher Somogyi	AES, Inc.
J. J. Song	University of California, San Diego
James Speck	Materials Department, University of California, Santa Barbara
Sridhar Srinivasan	Arizona State University
Ron Steen	Philips Lighting Electronics NA
Matthew A. Stough	OSRAM SYLVANIA
Peter Strasser	International Dark-Sky Association
Stephen Streiffer	Argonne National Lab Center for Nanoscale Material
Christopher Summers	PhosphorTech
Cristian Suvagau	BC Hydro-LDL
Jan Talbot	University of California, San Diego
Mark Thompson	University of Southern California
Paul Thurk	ARCH Venture Partners
Andrew Timmerman	Fairfield Crystal Technology
Mike Tischler	Ocis Technology
William Tumas	Los Alamos National Laboratory
Ralph Tuttle	Cree, Inc.
Yuan-Sheng Tyan	Eastman Kodak Company
Alexander Usikov	TDI, Inc.
James Van Hove	Albeo
Michael Vlademir	Navigant Consulting, Inc.
Philip von Guggenberg	SRI International
Karen Waldrip	Sandia National Laboratories
Stan Waldrop	Greenfield Capital
Wladek Walukiewicz	RoseStreet Labs Energy
George T. Wang	Sandia National Laboratories
King Wang	Agiltron, Inc.
Shaoping Wang	Fairfield Crystal Technology
Ronald Weber	Tyco Electronics
Ken Weidner	Dow Corning Corporation
Bernie Weir	ON Semiconductor
Fred Welsh	Radcliffe Advisors
Christian Wetzel	Rensselaer Polytechnic Institute (RPI)
Cindy Wills	WSU Extension Energy Program
Leonard Wojcik	Wojcik Technical Services
Dale Work	Philips Electronics

Zhihao Wu	Arizona State University
Jun Xu	Oak Ridge National Laboratory
Jiangeng Xue	University of Florida
Cungeng Yang	University of Utah
Angelo Yializis	Sigma Technologies International LLC
Arthur Young	American Bright Optoelectronics
Kin Man Yu	Lawrence Berkeley National Laboratory
Thomas Yuan	Cree, Inc.
Hank Zabawski	Heatron, Inc.
Steffen Zahn	Air Products & Chemicals, Inc.
David Zaziski	Nanosys Inc.
Yong-Hang Zhang	Arizona State University
Yi Zheng	OSRAM SYLVANIA
Teddy Zhou	Universal Display Corporation

APPENDIX B: DOE SSL Program Fact Sheets

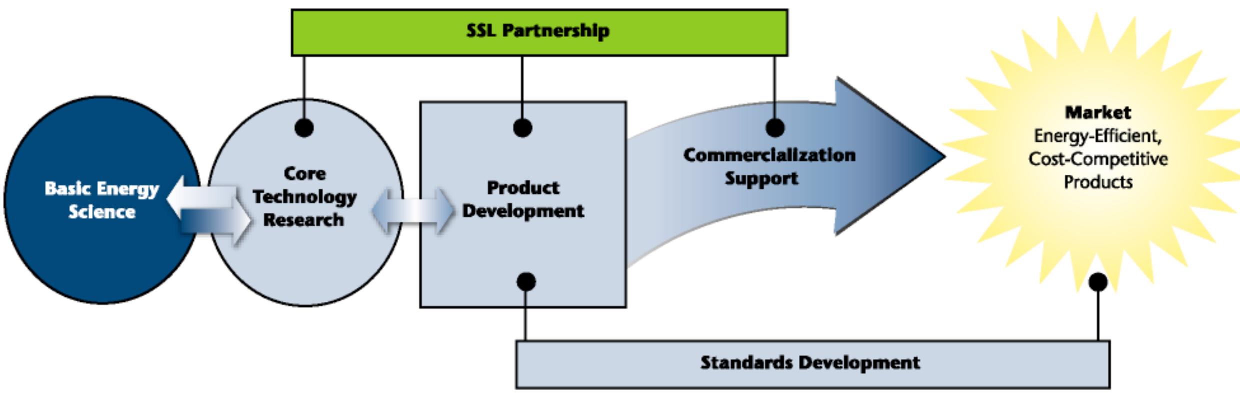
DOE Solid-State Lighting Portfolio

Guiding Technology Advances from Laboratory to Marketplace

The U.S. Department of Energy's solid-state lighting (SSL) portfolio draws on the Department's long-term relationships with the SSL industry and research community to guide SSL technology from laboratory to marketplace. DOE's comprehensive approach includes Basic Energy Science, Core Technology Research, Product Development, Commercialization Support, Standards Development,
and an SSL Partnership.

Basic Research Advances Fundamental Understanding. Projects conducted by the Basic Energy Sciences program focus on basic scientific questions that underlie DOE mission needs. These projects target principles of physics, chemistry, and the materials sciences, including knowledge of electronic and optical processes that enable development of new synthesis techniques and novel materials.

DOE SOLID-STATE LIGHTING PORTFOLIO



- DOE's **Basic Energy Sciences** program conducts basic research to advance fundamental understanding of materials behavior. Project results often have multiple applications, including SSL.
- **Core Technology Research** projects focus on applied research for technology development, with particular emphasis on meeting efficiency, performance, and cost targets.
- **Product Development** projects focus on using the knowledge gained from basic or applied research to develop or improve commercially viable materials, devices, or systems.
- To ensure that these investments lead to SSL technology commercialization, DOE has drawn on its ongoing relationships with the SSL industry and research community to develop appropriate **Commercialization Support** strategies.
- In addition, DOE is working with the National Electrical Manufacturers Association (NEMA), the Next Generation Lighting Industry Alliance (NGLIA), and other standards setting organizations to accelerate the **Standards Development** process.
- The **SSL Partnership** provides input to enhance the manufacturing and commercialization focus of DOE's SSL portfolio.

Core Technology Research Fills Knowledge Gaps. Conducted primarily by academia, national laboratories, and research institutions, Core Technology Research involves scientific research efforts to seek more comprehensive knowledge or understanding about a subject. These projects fill technology gaps, provide enabling knowledge or data, and represent a significant advance in our knowledge base. They focus on applied research for technology development, with particular emphasis on meeting technical targets for performance and cost.

Product Development Utilizes Knowledge Gains. Conducted primarily by industry, Product Development is the systematic use of knowledge gained from basic or applied research to develop or improve commercially viable materials, devices, or systems. Technical activities focus on a targeted market application with fully defined price, efficacy, and other performance parameters necessary for the success of the proposed product. Project activities range from product concept modeling through development of test models and field-ready prototypes.

Commercialization Support Activities Facilitate Market Readiness. To ensure that DOE investments in Core Technology Research and Product Development lead to SSL technology commercialization, DOE has also developed a national strategy to guide market introduction of SSL for general illumination. Working with the SSL Partnership and other industry and energy organizations, DOE is implementing a full range of activities, including:

- ENERGY STAR® designation for SSL technologies and products
- Design competitions for lighting fixtures and systems using SSL
- Technical information resources on SSL technology issues, test procedures, and standards
- Testing of commercially available SSL products for general illumination
- Coordination with utility, regional, and national market transformation programs
- Technology procurement programs that encourage manufacturers to bring high-quality, energy-efficient SSL products to the market, and that link these products to volume buyers

SSL Partnership Provides Manufacturing and Commercialization Focus. Supporting the DOE SSL portfolio is the SSL Partnership between DOE and the NGLIA, an alliance of for-profit lighting manufacturers. DOE's Memorandum of Agreement with NGLIA, signed in 2005, details a strategy to enhance the manufacturing and commercialization focus of the DOE portfolio by utilizing the expertise of this organization of SSL manufacturers.

The SSL Partnership provides input to shape Core Technology Research priorities, and accelerates implementation of SSL technologies by:

- Communicating SSL program accomplishments
- Encouraging development of metrics, codes, and standards
- Promoting demonstration of SSL technologies for general lighting applications
- Supporting DOE voluntary market-oriented programs

Standards Development Enables Meaningful Product Comparisons. The development of national standards and rating systems for new products enables consumers to compare products made by different manufacturers, since all companies must test their products and apply the rating in the same way.

No ratings or standards have yet been set for SSL products, but DOE is working closely with the Illuminating Engineering Society of North America, NEMA, NGLIA, and other standards setting organizations to accelerate development of needed standards and test procedures.

Coordinated Efforts Provide Enabling Knowledge to Advance SSL Technology

To accelerate solid-state lighting (SSL) technology developments, the U.S. Department of Energy leverages the strengths and capabilities of the Office of Science and the Office of Energy Efficiency and Renewable Energy (EERE).

- The Basic Energy Sciences (BES) program within the Office of Science conducts basic research to advance fundamental understanding of materials behavior, with the goal of impacting future directions in applied research and technology development.
- EERE's SSL portfolio guides technology advances from laboratory to marketplace with a comprehensive approach that includes Core Technology Research, Product Development, Commercialization Support, and Standards Development. Core Technology Research focuses on applied research for technology development, with the goal of meeting performance and cost targets.

Through coordination and collaboration, these DOE research programs are working together to provide the scientific foundation for new forms of lighting. In February 2006, BES held a Contractors' Meeting in conjunction with the DOE SSL Program Planning Workshop. BES researchers shared project updates on BES-supported fundamental research related to SSL. The workshop also included presentations on all DOE-funded SSL projects, providing a snapshot of DOE's SSL R&D portfolio and opportunities for further discussion and potential partnerships. In May 2006, BES hosted a workshop to focus specifically on identifying basic research needs and challenges that impact on energy-efficient SSL. The research directions identified at this workshop provided additional guidance for DOE planning.

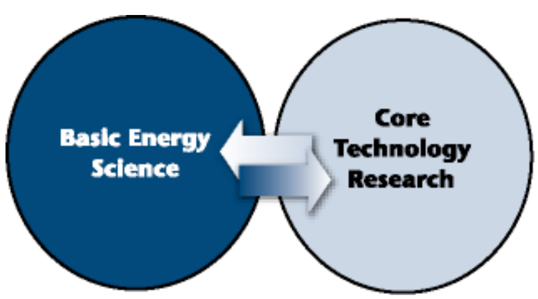
DOE SSL RESEARCH

Basic Research to Advance Fundamental Understanding

Focus
Basic scientific questions underlying materials behavior

Deliverables
Knowledge of physical, chemical, and materials sciences that enables development of new synthesis techniques and novel materials

Characterization capabilities to support these investigations



Applied Research for Technology Development

Focus
Technical targets for performance and cost

Deliverables
Materials and components for SSL technologies that meet efficiency, performance, and cost targets

Basic Research Advances Fundamental Understanding

BES projects focus on basic scientific questions that underlie DOE mission needs. These projects target principles of physics, chemistry, and the materials sciences, including knowledge of electronic and optical processes that enable development of new synthesis techniques and novel materials. BES encourages the development of results from its experimental and theoretical research programs and user facilities that will impact future directions in applied research and technology development. Project results often have multiple applications, including SSL.

Core Technology Research Focuses on Technical Targets

EERE's SSL portfolio draws on its long-term relationships with the SSL industry and research community, using a series of ongoing, interactive workshops to refine an extensive R&D agenda. This approach ensures that DOE funds the appropriate research topics that will improve efficiency and move SSL into the market. Input from these workshops helps to shape research priorities and the development of solicitations. Core Technology Research projects focus on applied research for technology development, with particular emphasis on improving the performance and durability of materials and components, as well as cost reduction.

DOE Drives Emphasis on Energy Efficiency

DOE's support of SSL is essential to ensure the development of *energy-efficient* SSL technology—an emphasis that, without DOE leadership, might be lost on the path to commercialization. The Department's involvement in SSL technology development pushes industry to higher levels of efficiency than they might otherwise achieve.

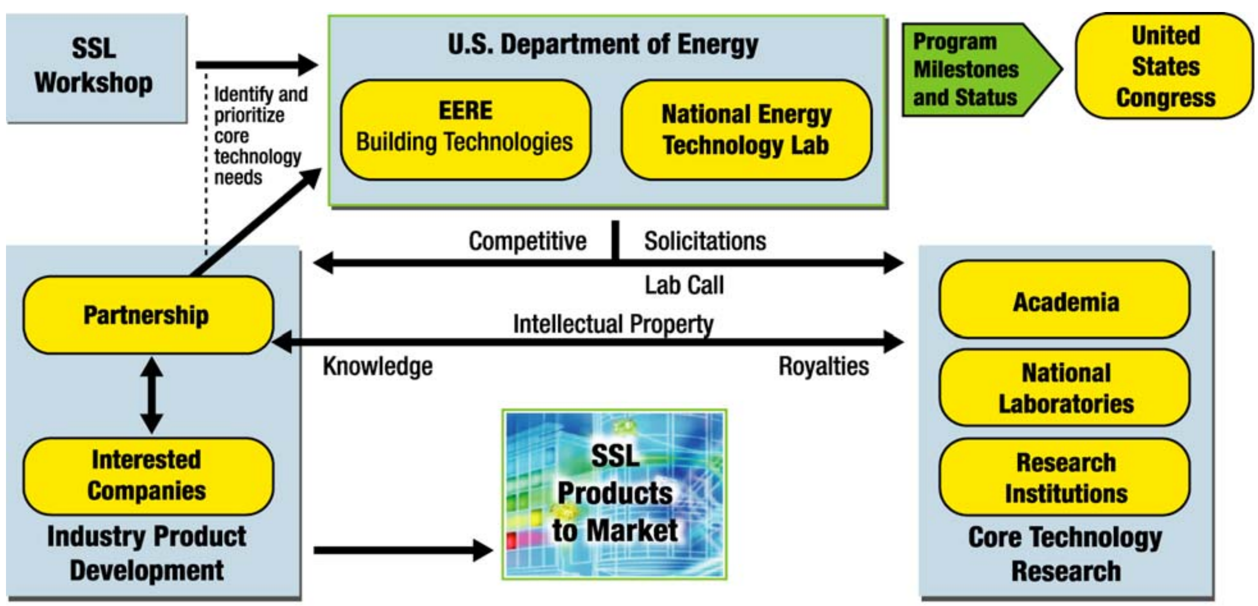
The Department's support also maintains our nation's technology leadership. While projected energy savings are significant, high-efficiency white-light sources represent a somewhat risky investment that industry is unlikely to fund exclusively. If our nation is to maintain its leadership position in SSL technology development, the U.S. must meet or exceed other countries' commitment to SSL initiatives. The results from DOE's collaborative projects will ultimately deliver substantial energy savings and position U.S. companies as global leaders in new lighting products, systems, and service markets.

Operational Plan for DOE SSL R&D

The U.S. Department of Energy (DOE) supports domestic research, development, demonstration, and commercial application of advanced solid-state lighting (SSL) technologies that are significantly more energy efficient than current lighting technologies. Guided by a Government-industry partnership, the mission is to create a new U.S.-led market for high-efficiency, general illumination products through the advancement of semiconductor technologies, to save energy, reduce costs, and enhance the quality of the lighted environment. The Department has set aggressive targets for SSL research and development (R&D): By 2025, to develop advanced SSL technologies that, compared to conventional lighting technologies, are much more energy efficient, longer lasting, and cost-competitive. DOE is targeting a product system efficiency of 50 percent with lighting that accurately reproduces sunlight spectrum.

DOE has structured an operational plan for SSL R&D (see Figure 1) that features two concurrent, interactive pathways. **Core Technology Research** is conducted primarily by academia, national laboratories, and research institutions. **Product Development** is conducted primarily by industry. Although the pathways and participants described here are typical, some cross-over does occur. For example, a product development project conducted by industry may include focused, short-term applied research, as long as its relevance to a specific product is clearly identified and the industry organization abides by the solicitation provisions. For more detailed definition of the SSL R&D pathways, see DOE's SSL website at *www.netl.doe.gov/ssl/definition.html*. The operational structure also includes innovative intellectual property provisions and a **SSL Partnership** that provides significant input to shape the Core Technology Research priorities.

OPERATIONAL PLAN FOR SSL R&D (Figure 1)



SSL Partnership. In 2004, DOE competitively selected an SSL Partnership composed of manufacturers and allies that are individually or collaboratively capable of manufacturing and marketing the desired SSL products. Partnership members must comply with pertinent DOE guidelines on U.S.-based research and product development. A key function of the SSL Partnership related to R&D is to provide input to shape the Core Technology Research priorities. As SSL technologies mature, any research gaps identified are filled through Core Technology Research—allowing the SSL industry to continue their development process, while much-needed breakthrough technologies are created in parallel. The Partnership members confer among themselves and communicate their individual research needs to DOE program managers, who in turn, shape these needs into the Core Technology Research solicitations.

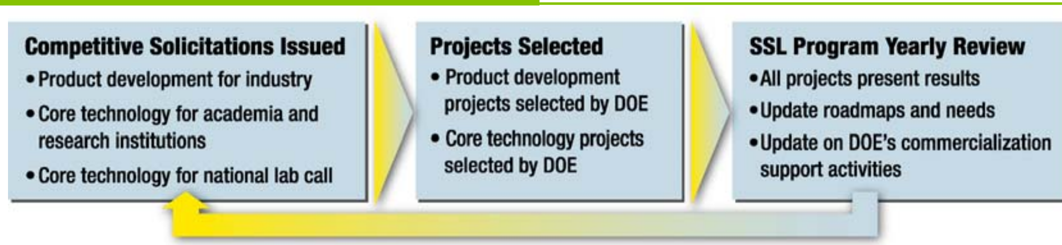
Product Development. DOE solicits proposals from interested companies (or teams of companies) for product development, demonstrations, and market conditioning. DOE expects these proposals to include comprehensive work plans to develop a specific SSL product or product family. Since the ultimate goal is to manufacture energy-efficient, high performance SSL products, each work plan should address the abilities of each participant or manufacturer throughout the development process. These offerors must not only have all the technical requirements to develop the desired SSL technology, but also must have reasonable access to manufacturing capabilities and targeted markets to quickly move their SSL product from the industry laboratory to the marketplace.

Core Technology Research. Core Technology Research provides the focused research needed to advance SSL technology—research that is typically longer-term in nature and not the focus of sustained industry investment. DOE funds these research efforts primarily at universities, national laboratories, and other research institutions through one or more competitive solicitations. Core Technology Research supports the SSL program by providing problem-solving research to overcome barriers identified by the Partnership. Participants in the Core Technology Research program perform work subject to what is termed an "exceptional circumstance" to the Bayh-Dole Act, and any resultant intellectual property is open, with negotiated royalties, to all Partnership members with a non-exclusive license. At DOE's discretion, Core Technology Research projects are peer-reviewed by Government personnel, independent organizations, and the SSL Partnership.

High-Level Timeline. Figure 2 details the high-level timeline for the SSL R&D operational plan. Each year, DOE expects to issue at least three competitive solicitations: the Core Technology Research Solicitation, Core Technology to National Labs (Lab Call), and the SSL Product Development Solicitation. A number of annual meetings are held to provide regular DOE management and review checks, and to keep all interested parties adequately informed. More specifically, these meetings:

- Provide a general review of progress on the individual projects (open meeting)
- Review/update the R&D plan for upcoming "statement of needs" in future solicitations (open meeting)
- At DOE's discretion, provide a peer review of Core Technology Research projects
- Provide individual project reviews by DOE

R&D OPERATIONAL PLAN PROCESS (Figure 2)



This document provides an overview of the high-level structure of the DOE SSL R&D program. More detailed program documents, such as annual solicitations and cooperative agreements, take precedence over information in this document.

Solid-State Lighting Patents Submitted as a Result of DOE-Funded Projects

As of January 2007, a total of fourteen solid-state lighting patents have been granted as a result of Department of Energy-funded research projects. This demonstrates the value of DOE SSL projects to private companies and notable progress toward commercialization. Since DOE began funding SSL research projects in 2000, a total of 64 patents applications have been applied for or awarded as follows: large businesses - 27, small businesses - 21, universities - 13, and national laboratories - 3.

Organization	Title of Patent Application (Bolded titles indicate granted patents)
Agiltron, Inc.	One patent application filed.
Boston University	Formation of Textured III-Nitride Templates for the Fabrication of Efficient Optical Devices (2)
	Nitride LEDs Based on Flat and Wrinkled Quantum Wells
	Optical Devices Featuring Textured Semiconductor Layers
Cree, Inc.	**Light Emitting Diode with Porous SiC Substrate and Method for Fabricating**
	Two other patent applications filed.
Fairfield Crystal Technology	Method and Apparatus for Aluminum Nitride Monocrystal Boule Growth
GE Global Research	**Light-Emitting Device with Organic Electroluminescent Material and Photoluminescent Materials**
	Luminaire for Light Extraction from a Flat Light Source
	Mechanically Flexible Organic Electroluminescent Device with Directional Light Emission
	Organic Electroluminescent Devices and Method for Improving Energy Efficiency and Optical Stability Thereof
	Series Connected OLED Structure And Fabrication Method
	Electrodes Mitigating Effects of Defects in Organic Electronic Devices
	Organic Electroluminescent Devices having Improved Light Extraction
	Hybrid Electroluminescent Devices
	OLED area Illumination Source
	Eight other patent applications filed.
Georgia Tech Research Corporation	One patent application filed.
International Technology Exchange	One patent application filed.

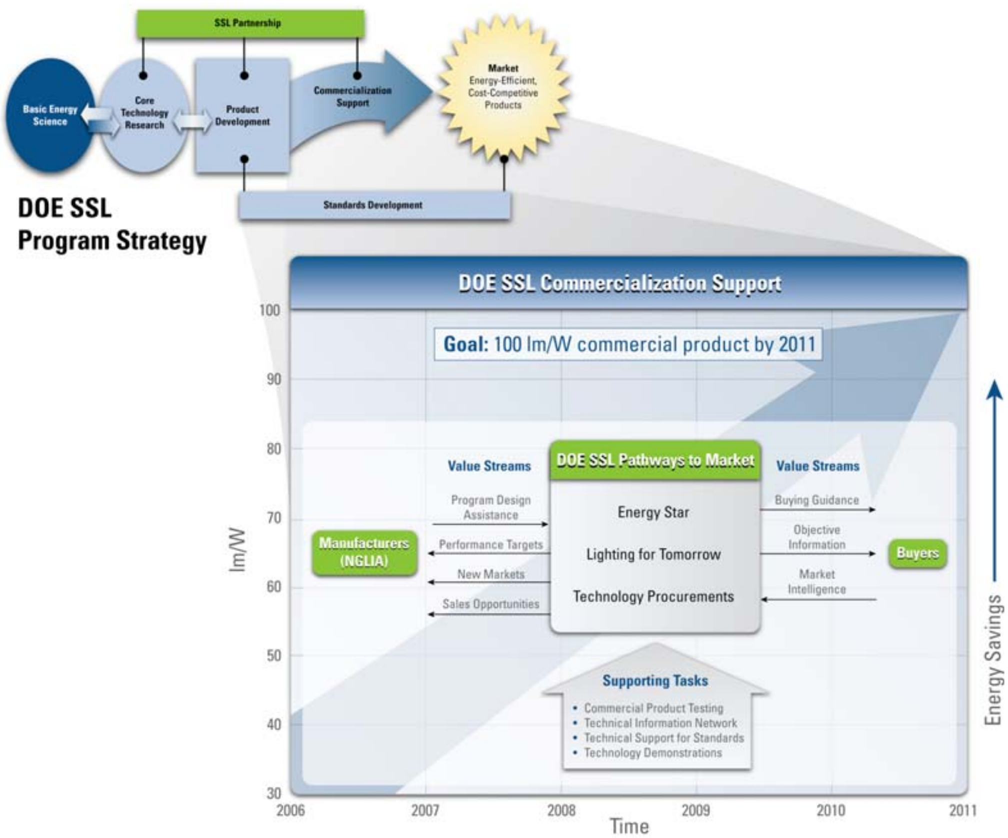
Light Prescriptions Innovators	Optical Manifold for Light-Emitting Diodes (2) Two other patent applications filed.
Maxdem Incorporated	Polymer Matrix Electroluminescent Materials and Devices
Nanosys	Nanocrystal Doped Matrices
OSRAM Opto Semiconductors, Inc.	Integrated Fuses for OLED Lighting Device Novel Method to Generate High Efficient Devices, which Emit High Quality Light for Illumination (2) OLED with Phosphors Polymer and Small Molecule Based Hybrid Light Source (2)
Pacific Northwest National Laboratory	Organic Materials with Phosphine Sulphide Moieties having Tunable Electric and Electroluminescent Properties One other patent application filed.
Philips Electronics North America	High Color-Rendering-Index LED Lighting Source using LEDs from Multiple Wavelength Bins Three other patent applications filed.
PhosphorTech Corporation	**Light Emitting Device having Selenium-Based Fluorescent Phosphor** **Light Emitting Device having Silicate Fluorescent Phosphor** **Light Emitting Device having Sulfoselenide Fluorescent Phosphor** **Light Emitting Device having Thio-Selenide Fluorescent Phosphor**
Sandia National Laboratories	**Cantilever Epitaxial Process**
Universal Display Corporation	**Binuclear Compounds** **Organic Light Emitting Device Structure for Obtaining Chromaticity Stability (2)** Stacked OLEDs Electrically Connected by A Reflective Electrode One other patent application filed.
University of California, San Diego	One patent application filed.
University of California, Santa Barbara	**Plasmon Assisted Enhancement of Organic Optoelectronic Devices** Silicone Resin Encapsulants for Light Emitting Diodes Four other patent applications filed.
University of Southern California	Fluorescent Filtered Electrophosphorescence

Guiding Market Introduction of High Efficiency, High-Performance SSL Products

The U.S. Department of Energy (DOE) has developed a comprehensive national strategy to guide solid-state lighting (SSL) technology from lab to market. To leverage DOE's $100 million investment in SSL technology research and development (R&D), and to increase the likelihood that this R&D investment pays off in commercial success, DOE has developed a commercialization support plan. The plan focuses DOE resources on strategic areas to move the SSL market toward the highest energy efficiency and the highest lighting quality.

DOE's plan draws on key partnerships with the SSL industry, research community, standards setting organizations, energy efficiency groups, utilities, and others, as well as lessons learned from the past. Commercialization support activities are closely coordinated with research progress to ensure appropriate application of SSL products, and avoid buyer dissatisfaction and delay of market development. The diagram below details the key components of DOE's commercialization support strategy, and how they relate to DOE's goals for luminous efficacy over time.

DOE SSL PATHWAYS TO MARKET



DOE SSL Pathways to Market

DOE supports three key pathways to market: ENERGY STAR®, the Lighting for Tomorrow Design Competition, and Technology Procurement. These pathways, described below, provide manufacturers with performance targets and information on new markets and sales opportunities. They provide buyers with objective information and purchasing guidance. In return, DOE partners including the Next Generation Lighting Industry Alliance (NGLIA) and the Technical Information Network provide feedback to guide DOE planning and program design.

ENERGY STAR for SSL. ENERGY STAR is a voluntary energy efficiency labeling program that helps consumers to identify products that save energy, relative to standard technology. DOE issued draft ENERGY STAR criteria for SSL luminaires in December 2006.

Lighting for Tomorrow Design Competition. In partnership with the American Lighting Association and the Consortium for Energy Efficiency, DOE sponsors Lighting for Tomorrow, a design competition that encourages and recognizes excellence in design of energy-efficient residential light fixtures. In 2006, a solid-state lighting competition was added to the existing program focused on compact fluorescent lighting (CFL) fixtures.

Technology Procurement. Technology procurement is an established process for encouraging market introduction of new products that meet certain performance criteria. DOE has employed this approach successfully with other lighting technologies, including sub-CFLs and reflector CFLs. DOE plans to employ technology procurement to encourage adoption of new SSL systems and products that meet established energy efficiency and performance criteria, and link these products to volume buyers and market influencers.

Additional Activities Support Primary Pathways

- **Commercial Product Testing Program.** DOE's SSL Commercial Product Testing Program provides unbiased information on the performance of commercially-available SSL products. The test results guide DOE planning for ENERGY STAR and technology procurement activities, provide objective product performance information to the public, and inform the development and refinement of standards and test procedures for SSL products.
- **Technical Information Network.** DOE's technical information network facilitates learning and promotes energy efficiency and quality in the deployment of SSL. The network, comprised of energy efficiency program sponsors, utilities, lighting researchers and designers, and others, will meet regularly to share technical information about SSL and to provide feedback from the market (retailers, builders, and consumers) on market needs and barriers.
- **Technical Support for Standards.** LEDs differ significantly from traditional light sources, and new test procedures and industry standards are needed to measure their performance. DOE provides leadership and support to accelerate the standards development process, facilitating ongoing collaboration among standards setting organizations and offering technical assistance in the development of new standards.
- **Technology Demonstrations.** DOE is planning SSL technology demonstrations in both the residential and commercial building sectors to provide real-life experience and data involving SSL installations in various applications. DOE will verify performance of the selected SSL products, including measurement of energy consumption, light output, color consistency, and interface/control issues. Demonstration results will inform DOE technology procurement activities and provide buyers with reliable data on product performance.

APPENDIX C: Background Material for R&D Priorities Breakout Session

DOE SSL R&D Tasks and Subtasks

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Background Material for R&D Priorities Breakout Session

February 1, 2007

DOE SSL R&D Tasks and Subtasks

2007 DOE Solid-State Lighting Workshop
Phoenix, Arizona

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Buildings Technologies Program

Foreword

The Department of Energy (DOE), working with a broad cross-section of stakeholders, created a comprehensive research and development (R&D) agenda, including tasks and subtasks, for its solid-state lighting (SSL) program. With input from stakeholders, DOE and the National Energy Technology Laboratory (NETL) identify "priority" subtasks from this list, which are subsequently funded under competitively-awarded solicitations.

At the 2005 DOE SSL Workshop in San Diego, participants prioritized the R&D agenda, identifying low-, medium-, and high-priority tasks and subtasks for 2005-2006. In 2006, DOE published the SSL R&D Multi-Year Program Plan (MYPP), which detailed metrics and milestones for high-priority areas of research.

Here in Phoenix, at the 2007 DOE SSL Workshop, DOE is asking participants to review and comment on proposed revisions of the tasks and priorities for the 2007 edition of the DOE SSL MYPP, Technology R&D Chapter. On Thursday afternoon, February 1st, the plenary session will be divided into four break-out groups, two on LED and two on OLED. The purpose of these break-out groups will be to review revisions to the tasks / subtasks as well as changes in priorities and metrics suggested by a technical working group comprised of representatives from the Next Generation Lighting Industry Alliance (NGLIA). DOE is soliciting input from all workshop participants on these revisions and changes in priority, as well as asking participants to comment on the R&D priorities for the next 1-2 years.

The attached document lists all the tasks and subtasks in the DOE's SSL program. Some of these subtasks are identified as "high priority", meaning they are considered the Department's highest SSL R&D priorities for the next 1-2 years. Some subtasks are identified as "medium priority" meaning they are expected to be the next group of high priorities, but are not yet ready to be funded. The remaining subtasks do not have an assigned priority, meaning they are on hold, waiting for technology breakthroughs and developments in other areas which may trigger a change in the DOE's priorities.

Request

Workshop participants are asked to review this document before the Thursday afternoon breakout sessions, focusing on the section of this document (either LED or OLED) for their break-out group. Participants are asked to:

- Review the draft priorities proposed by the NGLIA Team
- Suggest additional candidate subtasks for the priority lists
- Suggest deleting subtasks from the priority lists
- Modify or suggest new metrics / target values for the tasks

Participants should bring this reference document to the break-out sessions, to enable a more fruitful review and discussion of DOE's SSL R&D priorities for the next 1-2 years.

LED Core Technology Research – Subtask Priority Changes

Task 1.1: Inorganic Materials Research

Goal: increase internal quantum efficiency

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
Medium	**1.1.1**	Large-area substrates, buffer layers, and wafer research	Create efficient broadband semi-conducting materials. Develop lower defect density materials (GaN, ZnO substrates).			
High	**1.1.2**	High-efficiency semiconductor materials	Research includes: creating a more efficient green LED for a better color-mixing device, and examining the impact of doping on performance.	IQE[2]	20% green, 80% red, 40% blue	90%
High	**1.1.3**	Reliability and defect physics for improved emitter lifetime and efficiency	Research areas include: dopant and defect physics, device characterization and modeling, and investigation of droop (reduced efficiency at high temperature and current density) to increase lifetime while maintaining wavelength stability.	Lifetime and efficiency at high current density $\Delta\lambda/^{o}C$		50k hours and 150lm/W at 150A/cm^2
	1.1.4	Conversion Materials				

LED Core Technology Priority Changes

Relative to the top LED Core Technology priorities from the 2005 DOE Workshop in San Diego, the NGLIA/DOE are proposing the following changes:

<u>Moved to a lower priority</u>
1.1.1 Large-area substrates, buffer layers, and wafer research

<u>Added to a higher priority</u>
1.1.2 Reliability and defect physics for improved emitter lifetime and efficiency

<u>Modified</u>
- 2005 status was updated to 2006 values
- 1.1.3 added "while maintaining wavelength stability" to description

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[2] IQE and EQE status and projections assume pulsed measurements.

LED Core Technology Research – Subtask Priority Changes (continued)

Task 1.2: Inorganic Device Architecture Research and Modeling
Goal: increase external quantum efficiency

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
High	**1.2.1**	Device approaches, structures and systems	Work in this area is actually to increase extraction efficiency, but will be measured by progress in EQE.	EQE	50%	80 %
High	**1.2.2**	Strategies for improved light extraction and manipulation	Research into integrating optics into the chip, transport structures, device configuration, and reflector design.	Package efficiency	70%	90%

LED Core Technology Priority Changes

<u>Modified</u>

- 2005 status was updated to 2006 values

LED Core Technology Research – Subtask Priority Changes (continued)

Task 1.3: Inorganic Integration Technology Research
Goal: research technology for high performance LED lamps and luminaires

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
High	1.3.1	Phosphors and conversion materials	Research into high-efficiency phosphors suitable for LEDs, lumen maintenance issues, nanophosphor research.	Lumens/ optical Watt (phosphor)	200 lm/optical watt (@6000K and 75 CRI)	250 lm/optical watt (@4100K and 80 CRI)
Medium	1.3.2	Encapsulants and packaging materials	Create high temperature (~185C), long-life, UV-tolerant encapsulants and packaging materials. Also includes work to develop thermal management strategies and modeling of encapsulants.			
	1.3.3	Electrodes and interconnects	Ultra-low resistance, piezoelectric contacts			
Medium	1.3.4	Measurement metrics and color perception	Research in this area includes standardizing metrics to measure electrical and photometric characteristics of LED devices.			

LED Core Technology Priority Changes

Modified
- 2005 status was updated to 2006 values
- Changed Program Target from “230 lm/optical watt (@4100K and 80 CRI)” to “250 lm/optical watt (@4100K and 80 CRI)”

LED Core Technology Research – Subtask Priority Changes (continued)

Task 1.4: Inorganic Growth and Fabrication Processes and Manufacturing Research
Goal: cross-cutting improvements to growth and fabrication processes and manufacturing

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
Medium	1.4.1	Physical, chemical, optical modeling, measurement, and experimentation for substrate and epitaxial processes				
Medium	1.4.2	Design and development of in-situ diagnostic tools for the substrate and epitaxial process				
Medium	1.4.3	Research into low-cost, high-efficiency reactor designs and manufacturing methods				
Medium	1.4.4	Investigation (theoretical and experimental) of die separation, chip shaping, and wafer bonding techniques				

LED Product Development Research – Subtask Priority Changes

Task 2.1. Inorganic Materials and Device Architecture
Goal: increase internal and external quantum efficiency

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
	2.1.1	Substrate, buffer layer and wafer engineering and development				
High	**2.1.2**	High-efficiency semiconductor materials	Develop efficient broadband light emitting materials (including yellow-green, orange, and UV (360nm to 410nm)) and develop alternate low-cost materials (e.g., nitride materials)	IQE	20% green, 80% red, 40% blue	90%
Medium	**2.1.3**	Implementing strategies for improved light extraction and manipulation	Develop high refractive index encapsulants for improved light extraction and large-area light extraction and current injection			
	2.1.4	Device architectures with high power-conversion efficiencies	Chip scaling and micro-arrays; Multi-color chips, arrays on a single substrate			

LED Product Development Priority Changes
Relative to the top LED Product Development priorities from the 2005 DOE Workshop in San Diego, the NGLIA/DOE are proposing the following changes:

<u>Added to a higher priority</u>
2.1.2 High-efficiency semiconductor materials

<u>Modified</u>
- 2005 status was updated to 2006 values

LED Product Development Research – Subtask Priority Changes (continued)

Task 2.2. LED Component Technical Integration

Goal: develop cost-effective LED lamps and luminaires

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
High	2.2.1	Manufactured materials	Include phosphors and luminescent materials and high temperature encapsulants and mounting materials.[3]	% of original transmission per mm	85-90% (@150C and 10-15 kHrs)	95% (@150C Junction Temp. and 50 kHrs)[4]
Medium	2.2.2	LED packages and packaging materials	Solving problem of removing heat from the chip, delivering high-lumen output chips with ultra-low resistance contacts.			
High	2.2.3	Electronics Development	Research in this area includes developing lower cost electronics of smaller size with better color control and longer lifetime.	%Energy Conversion $/Watt X-step MacAdam Ellipse Lifetime	85% 0.50 $/Watt 7-step MacAdam Ellipse 20-50kHrs[5]	90+% 0.10 $/ Watt 4-step MacAdam Ellipse. 50kHrs
	2.2.4	Evaluate component lifetime and performance characteristics				

LED Product Development Priority Changes

<u>Moved to a lower priority</u>

2.2.2 LED packages and packaging materials

<u>Modified</u>

- 2005 status was updated to 2006 values
- 2.2.1 Removed metric: "Refractive index" and changed "percent transmission" metric to "% of original transmission per mm"
- 2.2.1 Added "and 50 kHrs" to Program Target
- 2.2.3 Changed description from "Research in this area includes developing lower cost electronics of smaller size with better color control (modulation)" to "Research in this area includes developing lower cost electronics of smaller size with better color control and longer lifetime."
- 2.2.3 Added metrics: "X-step MacAdam Ellipse" and "Lifetime"

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[3] NGLIA Technical Committee suggested breaking out this subtask as it represents several different types of materials efforts.

[4] This target may change to 185C as efficiency goals are met and cost becomes a higher priority

[5] Some 50kHr devices exist today, but these are presently military specification and are too costly for general illumination applications.

LED Product Development Research – Subtask Priority Changes (continued)

Task 2.3. System Technology Integration and Novel Luminaire Design

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
High	**2.3.1**	Optical coupling and modeling	Solving problem of extracting LED photons and getting them to desktop. This includes issues such as coupling to multiple sources and the multi-shadowing problem.	Optical/ Fixture Efficiency	70%	90%
	2.3.2	Mechanical design				
	2.3.3	Electronics development	Size, voltage, standardization, color control; Light engine versus luminaire electronics			
High	**2.3.4**	Thermal design	Solving problem of removing heat away from the emitter chip and reducing thermal resistance to keep LED device at a low operating temperature while integrating the packaged LED device into a luminaire.	Thermal resistance (Junction to case)	8-9 ºC per Watt	5ºC per Watt
	2.3.5	Evaluate human factors and metrics				
High	**2.3.6**	Evaluate luminaires lifetime and performance characteristics	Develop reliable information on lamp performance characteristics (e.g., lamp life, UV emission)	MTTF, (Mean time to failure)		

LED Product Development Priority Changes

Added to a higher priority

2.3.6 Evaluate luminaires lifetime and performance characteristics

Modified

- 2005 status was updated to 2006 values
- 2.3.1 Added "This includes issues such as coupling to multiple sources and the multi-shadowing problem." to description.
- 2.3.4 Added "while integrating the packaged LED device into a luminaire" to description

LED Product Development Research – Subtask Priority Changes (continued)

Task 2.4. Inorganic Growth and Fabrication Processes and Manufacturing Issues
Goal: develop equipment and tools for low-cost, high-yield manufacturing and scaling to larger wafers.

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
Medium	**2.4.1**	Incorporate proven in-situ diagnostic tools into existing equipment				
Medium	**2.4.2**	Develop low-cost, high-efficiency reactor designs				
Medium	**2.4.3**	Develop techniques for die separation, chip shaping, and wafer bonding				

OLED Core Technology Research – Subtask Priority Changes

3.1. OLED Materials Research

Goal: increase internal quantum efficiency through enabling physics and chemistry

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
	3.1.1	Substrate materials for electro-active organic devices				
High	**3.1.2, 3.2.2**	High-efficiency, low-voltage, stable materials and approaches to OLED structures between the electrodes for improved-performance low-cost white-light devices	This task involves material research encompassing stable hole and electron blocking layers and single and multi-layered devices to increase IQE. It also involves engineering between the electrodes (as opposed to chemistry), including layering the device for optimal efficiency.	IQE Voltage T70[6] at 1000 cd/m2	*Singlet:* B>20% W >20%, G >20% *Triplet:* G 100%, R 60% 4-5V	*Singlet*: 25% *Triplet*: 100% 2.8V T70 = 40,000 hrs
Medium	**3.1.3**	Improved contact materials and surface modification techniques to improve charge injection	This subtask includes research into n- and p- doped polymers and molecular dopants with emphasis on new systems and approaches to get charge into the device at the lowest possible voltage.			
Medium	**3.1.4**	Fundamental Science	This subtask involves research at the fundamental science level, including understanding and controlling singlet to triplet ratios to achieve 100% IQE and understanding degradation mechanisms to maximize lifetime.			

OLED Core Technology Priority Changes

Relative to the top OLED Core Technology priorities from the 2005 DOE Workshop in San Diego, the NGLIA/DOE are proposing the following changes:

<u>Combined as one task</u>

3.1.2 High-efficiency, low-voltage, stable materials *and*

3.2.2 Approaches to OLED structures between the electrodes for improved-performance low-cost white-light devices

<u>Modified</u>

- 2005 status was updated to 2006 values
- 3.1.2 Added “T70 at 1000 cd/m2” as metric and “T70 = 40,000 hrs” as Program Target
- 3.1.2 Added “2.8V” as Program Target

[6] Time it takes to reach 70% Lumen Maintenance.

OLED Core Technology Research – Subtask Priority Changes (continued)

3.2. OLED Device Architecture Research and Modeling

Goal: increase external quantum efficiency

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
High	**3.2.1**	Strategies for improved light extraction and manipulation	This subtask involves research into optical and device design for improving light extraction.	Extraction Efficiency	20%-30%	80%
High	**3.1.2, 3.2.2**	High-efficiency, low-voltage, stable materials and approaches to OLED structures between the electrodes for improved-performance low-cost white-light devices	This task involves material research encompassing stable hole and electron blocking layers and single and multi-layered devices to increase IQE. It also involves engineering between the electrodes (as opposed to chemistry), including layering the device for optimal efficiency.	IQE Voltage T70[7] at 1000 cd/m2	*Singlet:* B>20% W >20%, G >20% *Triplet:* G 100%, R 60% 4-5V	*Singlet*: 25% *Triplet*: 100% 2.8V T70 = 40,000 hrs
High	**3.2.3**	Research on low-cost transparent electrodes	This subtask involves research into better transparent electrode technology that offers an improvement over ITO cost and deposition rate and allows for roll-to-roll manufacturing	Ohms/□ Transparency $/m2	Flexible: 40 Ohms/□ 75-80%	Flexible: <10 Ohms/□ 92% < $1/m2

OLED Core Technology Priority Changes

<u>Added to a higher priority</u>

3.2.1 Strategies for improved light extraction and manipulation

<u>Combined as one task</u>

3.1.2 High-efficiency, low-voltage, stable materials *and*

3.2.2 Approaches to OLED structures between the electrodes for improved-performance low-cost white-light devices

<u>Modified</u>

- 2005 status was updated to 2006 values
- 3.2.1 Changed descriptor from "This subtask involves research into optical and device modeling for general illumination OLEDs" to "This subtask involves research into optical and device design for improving light extraction."
- 3.2.3 Added "and allows for roll-to-roll manufacturing" to description
- 3.2.3 Changed "ohm-cm" metric to "ohms/□" and "imaginary index k" metric to "transparency." Program Targets were changed accordingly

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[7] Time it takes to reach 70% Lumen Maintenance.

OLED Core Technology Research – Subtask Priority Changes (continued)

3.3. OLED Technology Integration

Goal: research technology for high performance OLED lamps and luminaires

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
	3.3.1	Down conversion materials				
Medium	**3.3.2**	Low-cost encapsulation and packaging technology	This subtask involves working on low-cost ways to seal the device to protect the luminaire from its environment to ensure a long device lifetime.			
	3.3.3	Electrodes and interconnects				
	3.3.4	Measurement metrics and human factors	Productivity, preference, and demonstrations; Standards for electrical and photometric measurement			

OLED Core Technology Priority Changes

<u>Moved to a lower priority</u>
3.3.2 Low-cost encapsulation and packaging technology

OLED Core Technology Research – Subtask Priority Changes (continued)

3.4. Organic Growth and Fabrication Processes and Manufacturing Issues
Goal: develop equipment and tools for low-cost, high-yield manufacturing

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
	3.4.1	Physical, chemical and optical modeling for fabrication of OLED devices				
High	**3.4.2**	Investigation (theoretical and experimental) of low-cost fabrication and patterning techniques and tools	This subtask includes modeling to understand the fabrication process and fundamentally improved fabrication processes.	Deposition Speed Material utilization		

OLED Core Technology Priority Changes

<u>Modified</u>

- 3.4.2 Added "and fundamentally improved fabrication processes" to description
- 3.4.2 Changed metric from "Cost of goods sold less materials cost" to "Deposition Speed" and "Material Utilization"

OLED Product Development Research – Subtask Priority Changes

4.1. OLED Materials Development

Goal: develop devices with increased internal quantum efficiency

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
High	**4.1.1**	Low-cost substrates	This subtask includes developing low cost, readily available substrates with a low water permeability and high thermal conductivity.	Cost Thermal conductivity %dark spot area		< $3/m2 10x <10% dark spots at T70[8]
High	**4.1.2, 4.2.2**	Between electrodes high-efficiency, low-voltage materials and architectures that improve device robustness, increase lifetime and increase efficiency.	This subtask involves developing architectures and materials that improve robustness, lifetime and efficiency and the optimization of materials that show mass production potential.	Efficacy[9] CRI EQE Voltage T70 at 1000 cd/m2	32 lm/W	>100 lm/W 90 2.8V T70 = 40,000 hrs
Medium	**4.1.3**	Improved contact materials and surface modification techniques to improve charge injection	Activities under this subtask include the refinement of currently available technologies and investigation of problems with the supply chain (i.e., improving the quality of material inputs for manufacturing).			

OLED Product Development Priority Changes

Relative to the top OLED Product Development priorities from the 2005 DOE Workshop in San Diego, the NGLIA/DOE are proposing the following changes:

<u>Combined as one task</u>

4.1.2 Between electrodes high-efficiency, low-voltage stable materials

4.2.2 Develop architectures that improve device robustness, increase lifetime and increase efficiency.

<u>Modified</u>

- 2005 status was updated to 2006 values
- Changed lumen maintenance metrics and targets from “T50” to “T70”
- 4.1.1 Changed subtask name from “Substrates for electro-active organic materials” to “Low-cost substrates”
- 4.1.2 and 4.2.2 Added 2.8V as Program Target

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[8] Task 4.3.1 “dark spots” at T50 assumes small uniformly distributed spots and no localized failure. Dark spots also include pixel shrinkage.

[9] This efficacy refers to an OLED device absent of any effort to improve light extraction efficiency.

OLED Product Development Research – Subtask Priority Changes (continued)

4.2. OLED Device Architecture Development

Goal: develop devices with increased external quantum efficiency

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
High	**4.2.1**	Implementing strategies for improved light extraction and manipulation	This subtask involves improving on known approaches for extracting light.	Extraction Efficiency	25-30%	90%
High	**4.1.2, 4.2.2**	Between electrodes high-efficiency, low-voltage materials and architectures that improve device robustness, increase lifetime and increase efficiency.	This subtask involves developing architectures and materials that improve robustness, lifetime and efficiency and the optimization of materials that show mass production potential.	Efficacy[10] CRI EQE Voltage T70 at 1000 cd/m2	32 lm/W	>100 lm/W 90 2.8V T70 = 40,000 hrs
Medium	**4.2.3**	Demonstrate device architectures: e.g., white-light engines (multi-color versus single emission)	Research in this area includes demonstrating a device that scalable.			

OLED Product Development Priority Changes

<u>Combined as one priority</u>
4.1.2 Between electrodes high-efficiency, low-voltage stable materials
4.2.2 Develop architectures that improve device robustness, increase lifetime and increase efficiency

<u>Modified</u>
- 2005 status was updated to 2006 values
- Changed lumen maintenance metrics and targets from “T50” to “T70”
- 4.1.2 and 4.2.2 Added 2.8V as Program Target

[10] This efficacy refers to an OLED device absent of any effort to improve light extraction efficiency.

OLED Product Development Research – Subtask Priority Changes (continued)

4.3. OLED Technology Integration

Goal: develop efficient and reliable OLED lamps and luminaires

Priority		Subtask	Short Descriptor	Metric	2006	Program Target (2015)
High	**4.3.1**	OLED encapsulation packaging for lighting applications	This subtask includes research in heat management, dissipation techniques, encapsulants, and down-conversion materials for maximizing high-quality lumen output and reduced water permeability.	$/m2 %dark spot area Loss penalty (compared to glass)	$4/m2	< $3 /m2 <10% dark spots at T70[11] 0%
	4.3.2	Simulation tools for modeling OLED devices				
	4.3.3	Voltage conversion, current density and power distribution and driver electronics				
	4.3.4	Luminaire design, engineered applications, field tests and demonstrations				

OLED Product Development Priority Changes

<u>Modified</u>

- 2005 status was updated to 2006 values
- Changed lumen maintenance metrics and targets from "T50" to "T70"
- 4.3.1 Added "and reduced water permeability" to descriptor

[11] Task 4.3.1 "dark spots" at T50 assumes small uniformly distributed spots and no localized failure.

OLED Product Development Research – Subtask Priority Changes (continued)

4.4. OLED Growth and Fabrication Processes and Manufacturing Issues

Goal: develop equipment and tools for low-cost, high-yield manufacturing

Priority	Subtask		Short Descriptor	Metric	2006	Program Target (2015)
High	4.4.1	Module and process optimization and manufacturing	This subtask involves inventing and adapting OLED manufacturing technologies to the needs of lighting. It also covers developing flexible substrates for roll-to-roll manufacturing.	Luminaire cost/m2		<$30/m2[12]
	4.4.2	Synthesis manufacturing scale-up of active OLED materials				
	4.4.3	Tools for manufacturing the lighting module				

OLED Product Development Priority Changes

<u>Moved to a lower priority</u>
1.1.3 Large-area substrates, buffer layers, and wafer research

<u>Added to a higher priority</u>
4.4.1 Module and process optimization and manufacturing

<u>Modified</u>
- 2005 status was updated to 2006 values
- 4.4.1 Changed descriptor from "Includes research into large-area coating and deposition and developing flexible substrates for roll-to-roll manufacturing." to "This subtask involves inventing and adapting OLED manufacturing technologies to the needs of lighting. It also covers developing flexible substrates for roll-to-roll manufacturing."

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[12] In order to be competitive with a fluorescent luminaire, OLEDs must cost less than or equal to this amount.

APPENDIX D: DOE Solid-State Lighting Program Commercialization Support Pathway

Solid State Lighting Program

Commercialization Support Pathway

U.S. Department of Energy

UPDATE -- January 2007

Building Technologies Program
Energy Efficiency and Renewable Energy
U.S. Department of Energy

I. SSL R&D Investment Leads to Technology Commercialization

The U.S. Department of Energy has a long-term commitment to develop and support commercialization of solid-state lighting (SSL) for general illumination, including sources, fixtures, electronics, and controls. Title IX (Research and Development) of the Energy Policy Act of 2005 (EPACT 2005) directs the Secretary of Energy to carry out a Next Generation Lighting Initiative (NGLI) to support research, development, demonstration, and commercial application activities for SSL.

The Secretary is also directed to carry out research, development, demonstration, and commercial application activities through competitively selected awards. The Energy Act authorizes $50 million to the NGLI for each fiscal year 2007 through 2009, with extended authorization to allocate $50 million for each of the fiscal years 2010 to 2013. Actual appropriations are subject to the Congressional appropriations process.

This public R&D investment serves the ultimate goal to successfully commercialize the technologies in the buildings sector, where lighting accounts for more than 20 percent of total electricity use. Potential benefits are enormous if SSL technology achieves projected price and performance levels:

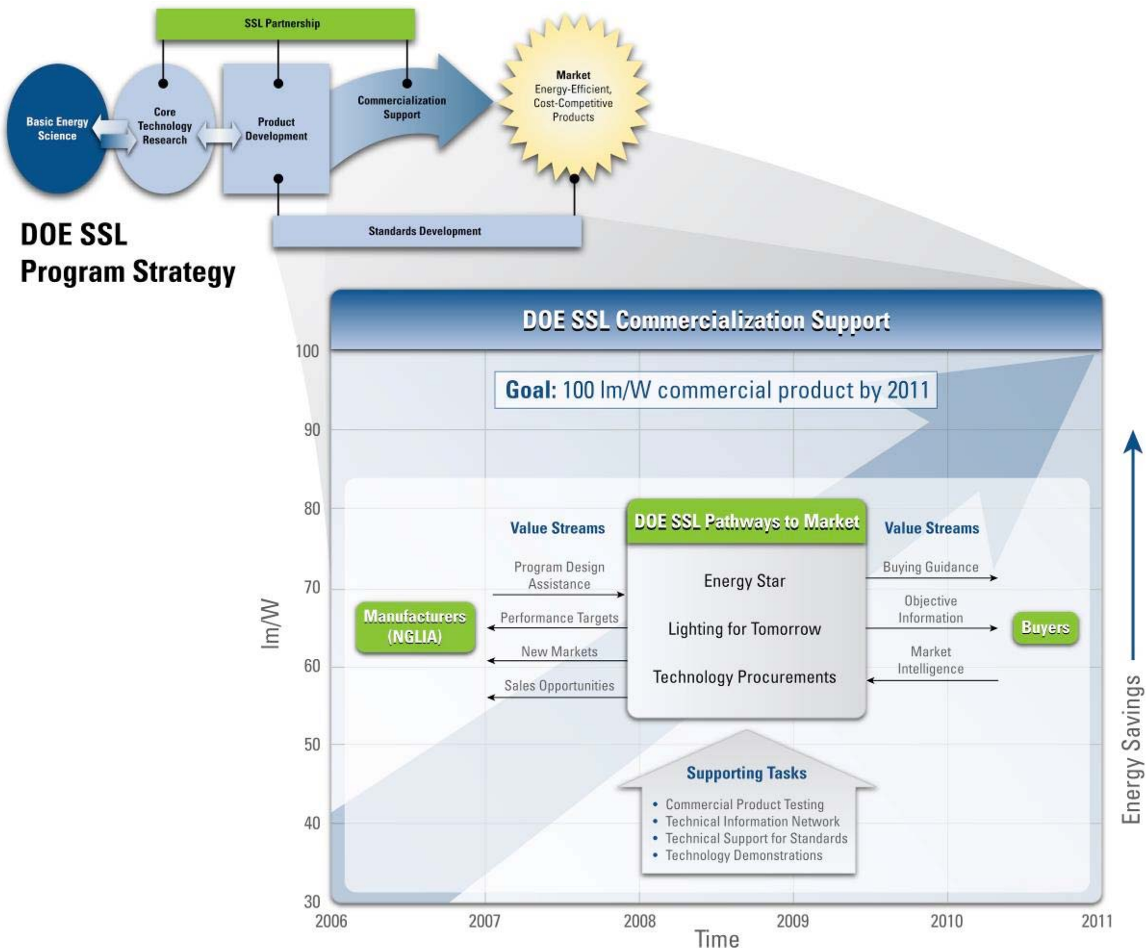
- In 2027, the annual energy savings from solid-state lighting would be approximately 348 terawatt-hours, or the equivalent annual electrical output of 44 large power plants. At today's energy prices, that would equate to more than $30 billion in energy savings in that year alone.
- Total electricity consumption for lighting would decrease by roughly 33 percent relative to a scenario with no SSL in the market. These electricity savings are greater than the energy consumed to illuminate all the homes in the US today.
- Over the 20 year period from 2007 to 2027, cumulative energy savings are estimated to total about 3,019 terawatt-hours, representing about $280 billion in cumulative energy savings at today's energy prices.

To realize the full promise of SSL, major research challenges must be addressed. DOE has a comprehensive strategy to accelerate the development and market introduction of energy-efficient white-light sources for general illumination. The figure below illustrates DOE's SSL Program Strategy. Unique attributes of SSL technologies underscore the importance of a long-term, coordinated approach encompassing applied research and strategic technology commercialization support.

Effective market introduction of SSL technologies must be informed by and coordinated with the applied research currently underway. Recent R&D advances have pushed white-light LED performance to levels that make them appropriate for use in some general illumination applications. DOE's commercialization support plan draws on a variety of strategies to assist the market introduction of high-quality, energy-efficient SSL technologies.

II. Commercialization Support Activities

DOE is actively engaged in activities that support the commercialization of SSL technologies for use as general illumination sources. As a public agency DOE is able to provide support and guidance in several areas that move the SSL market toward the highest energy efficiency and highest lighting quality. DOE's on-going partnership with the SSL industry helps to connect R&D and product development activities to the market. DOE has organized its commercialization support activities in terms of pathways to the market, and supporting tasks needed to facilitate those pathways. The figure below expands the Commercialization Support area, showing the relationship of the activities to the luminous efficacy goals over time.



SSL Industry Partnership

EPACT 2005 directed DOE to partner, through a competitive selection process, with an industry alliance representing US-based SSL research, development, infrastructure, and manufacturing expertise. The legislation further directed DOE to seek industry input in identifying SSL technology needs, assessing the progress of research activities, and updating SSL technology roadmaps. In fulfillment of this directive, DOE signed a Memorandum of Agreement with the Next Generation Lighting Industry Alliance (NGLIA) in 2005. Alliance members include the major US-based manufacturers of LEDs, OLEDs, components, materials, and systems. Membership continued to grow in 2006, including increased participation by lighting fixture manufacturers. The Alliance provides regular feedback to DOE through bimonthly meetings, and has several topical subcommittees that provide technical input to support DOE activities such as the development of ENERGY STAR® criteria for SSL products, development of standards and test procedures, and updates to the DOE SSL R&D Multi-Year Program Plan.

A. Pathways to Market

DOE is engaged in three key activities that serve as pathways to market for energy-efficient SSL technologies, as described below. These pathways speed introduction and adoption of energy-efficient technologies by providing a competitive advantage to products that are more efficient compared to standard technology.

ENERGY STAR for SSL

ENERGY STAR is a voluntary energy efficiency labeling program that helps consumers to identify products that save energy, relative to standard technology. <u>DOE issued draft ENERGY STAR criteria for solid-state lighting (SSL) luminaires in December 2006.</u> The proposed criteria include two categories: Category A covers a limited number of general illumination niche applications for which white LED systems are appropriate in the near-term, and Category B, which is intended to cover a wide range of LED systems for general illumination. Category B will serve as the longer term target for the industry. Initial applications eligible under Category A include those with the following characteristics: 1) appropriate for a light source with a directional beam, as opposed to a diffuse source; 2) low to moderate illuminance requirement; 3) illuminated task or surface relatively close to the light source; and 4) potential for cost-effective use of LED-based products in the near term. Initial Category A applications are: undercabinet lighting, portable desk/task lights, outdoor porch, pathway, and step lighting, and recessed downlights. For more information and ongoing updates, see: http://www.netl.doe.gov/ssl/energy_star.html.

Lighting for Tomorrow

DOE is one of the organizing sponsors of Lighting for Tomorrow (LFT), along with the American Lighting Association and the Consortium for Energy Efficiency. Lighting for Tomorrow is a design competition that encourages and recognizes excellence in design of energy-efficient residential light fixtures. In 2006, an SSL competition was added to the existing program for CFL-based lighting fixtures. Winners of the initial SSL competition were announced in December, including kitchen undercabinet light fixtures, portable desk/task lights, and outdoor lighting, all using white LEDs as the light source. Winning companies included Progress Lighting, American Fluorescent, Lucesco, and Lucere Lighting. Lighting for Tomorrow will continue in 2007, again with separate categories for CFL-based fixture families and LED-based fixtures. Information is available at www.lightingfortomorrow.com.

Technology Procurement

Technology procurement is an established process for encouraging market introduction of new products that meet certain performance criteria. DOE has employed this approach successfully with other lighting technologies, including sub-CFLs and reflector CFLs. DOE plans to employ technology procurement to encourage new SSL systems and products that meet established energy efficiency and performance criteria, and link these products to volume buyers and market influencers. Volume buyers may include the federal government (FEMP, DLA, GSA), utilities, or various sub-sectors including hospitals, lodging, or retail. This activity is linked closely to the technology demonstrations described below. For more information and ongoing updates on technology procurement and demonstration activities, see: http://www.netl.doe.gov/ssl.

B. Supporting Tasks

The pathways to market described above are underpinned by several supporting tasks. The results of these tasks feed directly into the pathway activities.

Commercial Product Testing Program

SSL technologies today are undergoing rapid change and improvements, and products arriving on the market exhibit a wide range of performance. There is a need for reliable, unbiased product performance data to allow potential users to compare SSL products to traditional technologies, to reveal technical and design problems, and to inform the performance expectations of the pathway activities, as well as the standards processes. DOE initiated the Commercial Product Testing Program with a pilot round in which four commercially-available LED-based lighting fixtures were tested for total luminous flux, luminous intensity, wattage, and color characteristics. The program was officially kicked off during a half-day workshop on October 27, 2006 and is testing 8 to 10 products per quarter. DOE allows test results to be distributed in the public interest for noncommercial, educational purposes only. Detailed test reports are provided to users who provide their name, affiliation, and confirmation of agreement to abide by DOE's "No Commercial Use Policy." For more information and ongoing updates, see: http://www.netl.doe.gov/ssl/comm_testing.htm.

Technical Information Network

SSL is a rapidly changing technology and is new to many in the lighting and energy efficiency professions. To facilitate learning and promote ongoing emphasis on energy efficiency and quality in the deployment of SSL, DOE is establishing a technical information network. The network will involve energy efficiency program sponsors, utilities, lighting researchers and designers, and others with interest in lighting energy efficiency. The network will meet regularly to receive technical information about SSL, and to provide feedback from the market, including retailers, builders, and consumers, on market needs and barriers. DOE has already developed a series of fact sheets addressing technical and applications issues related to use of white LEDs as a general illumination source. These fact sheets and web-based materials are updated regularly to reflect the rapid development of the technology, and new topics are under development. Members of the Network will adapt and disseminate these technical materials to their local constituencies. For more information and ongoing updates, see: http://www.netl.doe.gov/ssl.

Technical Support for Standards
Because LEDs differ significantly from traditional light sources, new test procedures and industry standards are needed to measure their performance. To help coordinate and accelerate the standards development process, DOE hosted workshops in March and October 2006 bringing together all of the relevant standard-setting organizations. New or revised procedures and standards are currently under development to measure luminous flux, luminous intensity, lumen depreciation, and color characteristics of white-light LEDs. The new standards are expected to be published in mid-2007. For more information and ongoing updates, see: http://www.netl.doe.gov/ssl/standards_dev.html.

Technology Demonstrations
DOE is planning SSL technology demonstrations in both the residential and commercial building sectors. Currently in the product and host site identification phase, the demonstrations are expected to be implemented later in 2007. These demonstrations will provide real-life experience and data involving SSL installations in various applications. DOE will verify performance of the selected SSL-based products, including measurement of energy consumption, light output, color consistency, and interface/control issues. The technology demonstrations will also play a critical role in the technology procurement process, providing the performance verification needed to secure large volume purchases of SSL-based products. For more information and ongoing updates on technology demonstration activities, see: http://www.netl.doe.gov/ssl.

January 2007